TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 30 JUNE 1949 Number 3

ELEVENTH AWARD OF THE WILLIAM BOWIE MEDAL

CITATION

Leo Otis Colbert

Mr. President: It gives me great pleasure, on behalf of the Committee on the Award of the William Bowie Medal, to recommend the bestowal of this medal on Dr. Walter Davis Lambert, formerly Chief of the Section of Gravity and Astronomy, Division of Geodesy, United States Coast and Geodetic Survey, in which organization he served for 40 years.

Dr. Lambert has been an untiring leader in the field of theoretical geodesy for over a quarter of a century and is considered by many as the top American authority in this field. His work in Earth Sciences includes studies of figure of the Earth determinations and the application of lunar occultations to determination of relationships between continental geodetic datums. He has investigated the relationship between gravity and the deflection of the vertical. He has promoted observations and studies of the variation of the polar axis. He is the foremost authority on Earth tides, those small movements in the Earth's crust due to the same forces as produce the sea tides.

Walter Davis Lambert
Recipient, Eleventh Award of the William Bowie Medal
April 20, 1949 (Photo by Harris and Ewing)

Dr. Lambert is the author of more than 60 published papers covering the whole field of Earth Sciences. He is the author of the article on Geodesy in the Encyclopedia Britannica, and of six publications of the United States Coast and Geodetic Survey on geophysical sciences.

His high reputation is by no means confined within the borders of this country but has spread throughout the scientific world. Dr. Lambert has made available the fruits of his efforts by associating himself with many scientific organizations in which he has held many responsible offices. He has been President of the Section of Geodesy of the American Geophysical Union, President of the Philosophical Society of Washington, and Vice-President of the Washington Academy of Sciences. He has been President of the International Association of Geodesy since 1946. At the meeting of this Association in Oslo last August he was re-elected to that office for a second three-year term.

Dr. Lambert has represented his country in many international meetings for geodesy and astronomy, and his guidance and wisdom have been a tower of strength to his associates, to his organizations, and to the science of geodesy.

RESPONSE AND ACCEPTANCE BY WALTER D. LAMBERT

Mr. President, Admiral Colbert, Ladies, and Gentlemen: It is with pleasure that I accept the honor that has just been conferred upon me. The pleasure is all the greater in that so much of my work was done under the immediate direction of William Bowie, for whom this Award is named. It is an enduring memorial to Bowie's services to science in general and to geophysics in particular.

In the specifications for awarding the Medal something is said about cooperation. Now cooperation involves more than one person. The psychologists tell us that there exist split personalities, so that it might be something of an achievement for one man to induce the several selves within himself to cooperate towards some fruitful end, but it seems unlikely that the Bowie Medal Committee had cases of this sort in mind.

When there is cooperation in the accepted sense, there is always a group of persons involved, be that group small or large. Though it may be impracticable to award a medal to anything so elusive as a group, nevertheless the group should have some recognition.

For the past 40 years and more I have been associated with the United States Coast and Geodetic Survey. Such work as I have done there could not have been done without the acquiescence and indeed active encouragement of my immediate chiefs; for the first years, Leland P. Shidy and Rollin A. Harris and then over a long period William Bowie, for whom this Award is named. I mention by name only the dead. Then there were his successors. These in turn had the approval and encouragement of the various Directors of the Survey.

I have drawn freely on the advice and experience of others and for the last five years of my normal connection with the Survey I have had the valuable assistance of the members of the Section of Gravity and Astronomy, of which I was Chief. To all these I owe my thanks and a full recognition of the credit that is due them for the Award that I now receive.

My work has in the main been a pleasure to me, a boon not given to every man--at least not on this side of Utopia. I trust that my strength will endure for a while longer, so that I may continue my work and my happiness in it, and thus perhaps still achieve something worthwhile. Again I thank you all.

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

GRAVIMETRIC DEFLECTIONS BY THE METHOD OF CONDENSATION

Donald A. Rice

Abstract--The current United States Army Map Service-United States Coast and Geodetic Survey project for determination of gravimetric deflections is discussed. Essential elements of the condensation method of reducing gravity values are given, followed by results of preliminary tests of the method as applied to two astronomic-geodetic stations in north Texas.

Investigation of the relationship between gravity anomalies and deflection of the vertical has been in progress at the United States Coast and Geodetic Survey for several years [LAMBERT, 1947]. In view of the increasing importance of this approach in the solution of world-wide mapping problems, the Army Map Service in 1947 requested the Survey to expedite the investigation and arranged a transfer of funds for the purpose. This enabled regular assignment of personnel to the project and provided for intensive effort to obtain and process gravity data from commercial sources in the United States. Field work in previously unsurveyed areas is also being financed under this arrangement.

Contacts with commercial sources of gravity data were established originally through the Research and Development Board in 1947. Many oil and exploration companies have indicated willingness to contribute data for the project, in most cases on a confidential basis in view of the high competitive value of the data requested. As of April 1948, gravity data had been received from the Brown Geophysical Company, Gulf Research and Development Company, Shell Oil Company, Standard Oil Company of New Jersey, and Humble Oil and Refining Company. Special acknowledgment is also made of the cooperation of George P. Woollard in supplying regional gravity values obtained in geological studies in the eastern United States.

A large part of the gravity data available at the present time is centered in a nearly continuous area of 700,000 sq mi in the south-central United States. Gravity-station spacing in this area varies from three to ten miles, and the total number of stations is about 25,000, of which 15,000 are located in portions of Texas and Oklahoma at an average three-mile spacing. The latter data, furnished by the Brown Geophysical Company, provide a sufficiently extensive gravity net for preliminary tests of the gravimetric method pending the processing of remaining data on hand.

To determine gravimetric deflections it is required that observed gravity be reduced to the geoid surface and that this surface include all attracting matter [VENING MEINESZ, 1928]. Although there are several methods of satisfying that requirement, this paper is confined to the method of condensation as used in the current project [HELMERT, 1902; LAMBERT, 1930]. For convenience, the essential features of this method are repeated here. The topography of density δ is compressed into a surface layer on the geoid. Assuming the topography to be an infinite slab of thickness equal to h (the elevation of the observation point), the surface density of this condensed layer then becomes $h\delta$ (see Fig. 1). Attraction of the layer on the point P remains the same as that of the original slab [PRATT, 1871]. However, this condensation changes the situation in two respects. First, it raises the geoid slightly because the transference of attracting matter causes increased horizontal attraction along the level surface; this effect is small and easily computed. Second, it makes necessary the application of the terrain correction (Geländereduktion) to provide for the increased attraction of the condensed slab as compared with the actual terrain. There still remains the free-air reduction from P to Q which is made in the usual manner, except in cases where a significant departure from the normal gradient is indicated by the topography and its compensation. If the gravity field is located in reasonably level country, the geoid warping due to condensation is small enough to be neglected. Likewise the terrain correction and the departure from normal vertical gradient are quite small and non-systematic in effect on the deflections. For this type of terrain the condensation and free-air reduction methods can therefore be assumed equivalent.

In rugged terrain the additional corrections must be considered. Geoid warping may amount to a meter or two in extreme cases, the terrain correction may exceed + 50 mg, and the correction for departure from normal vertical gradient may be of the order of -5 to -10 mgal.

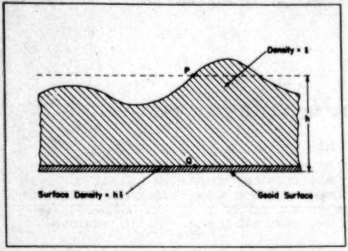

Fig. 1--Gravity reduction by condensation on geoid surface

Computation of basic tables for gravimetric deflections has been completed by the Coast and Geodetic Survey [SOLLINS, 1947]. The extent and flexibility of these tables permit wide choice of method, with ample accuracy.

Gravimetric deflections are derived by mechanical quadrature solution of a double integral having radial distance and direction as variables. The mean anomaly in a small element of area is assumed to be constant throughout the element. Using the tables referred to above, transparent templates are so constructed that each compartment has a radial deflection effect of 0.001 sec for one mgal anomaly. The total effect for each sector is found by summation and resolved into meridian, ξ, and prime-vertical, η, components. With these templates, one reading of the mean anomalies gives both components, with considerable saving of time over other types of templates which require separate readings for each.

Processing and plotting of gravity anomalies in Texas and Oklahoma have progressed to a point where the gravimetric method may be tested by comparison with astronomic and geodetic data. The results presented here are for two astro-geodetic stations in north Texas. The location of these stations, Roby and Polk, permits accurate anomaly readings to a distance of 111 mi from each; the astro-geodetic deflections differ greatly although the stations are only about 87 mi apart. At Roby the deflection in latitude is +2.89 sec while at Polk the deflection is -3.34 sec; prime-vertical deflections are -2.73 sec and +0.68 sec, respectively. Examination of topography in the immediate area shows nothing to cause such deflection differences; the estimated local topographic-isostatic deflection effect would be small at each station, with no indication that even the signs would agree with the astro-geodetic evidence. It is obvious that these rather large deflection differences are due to subsurface density variations.

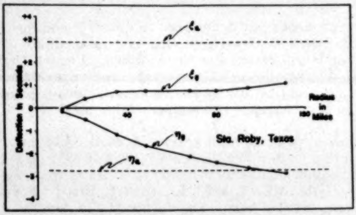

Fig. 2--Comparison of astro-geodetic and gravimetric deflections at station Roby

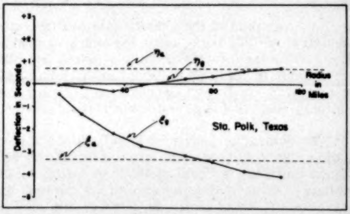

Fig. 3--Comparison of astro-geodetic and gravimetric deflections at station Polk

We now examine each station separately. Gravimetric deflections denoted by the g subscript in the sense astronomic minus geodetic are plotted accumulatively against radius of gravity field utilized; astro-geodetic deflections, denoted by the subscript a, are represented by horizontal dashed lines (see Fig. 2 and 3). At station Roby the gravimetric deflections for the full 111-mile radius differ from the astro-geodetic values by 1.82 sec in latitude and 0.17 sec in the prime vertical. At station Polk, the differences are 0.68 and 0.02 sec, respectively. In addition to the usual errors of the astro-geodetic determinations (probably less than 0.5 sec in each component) there are two major causes for these differences. First, the gravity field is too limited in extent to give highly accurate deflections in the absolute sense. Second, the geodetic datum is uncertain when considered as an absolute value. However, the gravimetric and astro-geodetic deflection differences in the sense Roby minus Polk should agree quite closely, since the effects of neglected gravity zones would be nearly the same on both stations and any geodetic datum error would be substantially canceled out. These deflection differences are now plotted against radius of gravity field and the agreement is graphically shown in Figure 4. The progressive approach of the gravimetric $\Delta\xi$ curve to the astro-geodetic line gives rather strong indication that an additional radial distance of 50 mi or so

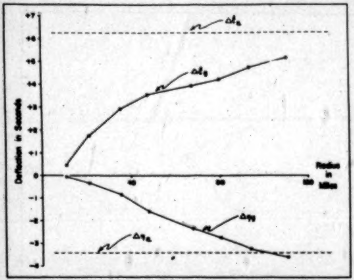

Fig. 4--Comparison of astro-geodetic deflection differences (Roby minus Polk) with corresponding gravimetric values

would produce an agreement between the two values comparable to that already shown in the case of the prime-vertical deflections. Whatever residuals then remained could be ascribed principally to uncertainties in the astro-geodetic data and to the small effect of the gravity gradient immediately around the deflection stations. Accurate determination of this gradient could not be made due to the lack of close-spaced gravity values; the effect was estimated to be less than 0.2 sec in each component.

Anomalies used in the gravimetric analysis of stations Roby and Polk were computed in accordance with the International Gravity Formula which is based on parameters of the International Ellipsoid [LAMBERT, 1945]. Since the astro-geodetic deflections at these stations are derived from triangulation developed on the Clarke ellipsoid of 1866, they are not strictly comparable to the deflections obtained gravimetrically. However, as a consequence of the comparatively small radius of gravity field utilized in this test, divergence between the two ellipsoids had an effect of less than 0.1 sec on the comparison of meridian deflections at Roby and Polk, and practically no effect on the prime-vertical deflections at these stations. Where more extensive gravity fields are utilized, the two systems must be reduced to a common basis for comparison.

A generalized free-air anomaly map of the area indicates the reason for large deflection differences between Roby and Polk (see Fig. 5). The main feature is a large negative belt with its east-west axis nearly passing through Roby and its north-south axis nearly intersecting Polk. Proximity of this feature to Polk deflects the plumb line northward with a resulting large negative deflection in the meridian. The prime-vertical deflection at Polk is little affected by this feature due to its symmetrical position about the north-south line. At Roby the situation is reversed; the feature has little effect in latitude due to symmetry, but has a pronounced effect in the prime vertical, deflecting the plumb line westward. It is noteworthy that the effect of this feature is not apparent in a topographic-isostatic deflection determination.

As suspected previously, and as demonstrated by the current investigations, the more distant zones cannot be ignored if accurate absolute deflections are to be obtained. KASANSKY [1935] estimates the effect of distant zones to be of the order of one second based on results of the Russian investigations of the early 1930's using a gravity field of 70-mile radius. Other investigators, notably DE GRAFF HUNTER [1935], ascribe somewhat more importance to the distant zones. Further work, based on the gravity data now being assembled, will be necessary to establish reliable criteria for application of the gravimetric method. Assuming a random mean anomaly value of ± 50 mgal for the zones neglected in analysis of Roby and Polk, the probable error in absolute deflection caused by neglecting these zones comes to about one second. A considerably larger error would result from a non-random arrangement of mean anomalies in the neglected zones.

It should be noted that as distance from the deflection station increases, the individual zone areas rapidly become larger. For example, with the present system of template subdivision a radial distance of 111 mi includes one half of the total number of compartments covering the entire Earth's surface, each having the same effect on the deflection for a given anomaly value. Larger zones in general seem to indicate an approach toward random distribution, thereby diminishing the net effect at the deflection station. Stations located in or near mountainous regions or close to ocean deeps require more extensive gravimetric surveys since a systematic pattern of anomalies would persist throughout a larger number of compartments.

Before means were developed for making accurate and extensive gravity surveys, it was possible to determine independent deflections of the vertical only by assigning certain densities to the visible topography and by making assumptions as to density distribution throughout the Earth's crust. Past experience and the examples given here indicate these assumptions can often result in errors as great as, or greater than, the deflections themselves. Using the method originally developed by Stokes and expanded by Vening Meinesz, De Graff Hunter, **Kasansky**,

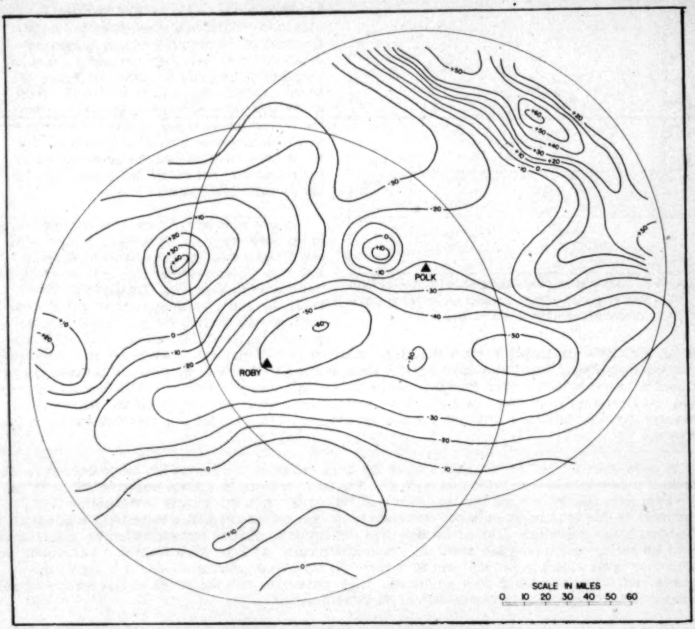

Fig. 5--Generalized free-air anomaly contour map of area used in analysis of stations Roby and Polk

Lambert, and others in recent years, we can now make use of observations of the intensity of gravity, very dense close to a station and gradually thinning out as the distance increases. From a gravity survey of this type, more accurate deflections of the vertical can be derived. Increased accuracy, as compared with the older method, results from ability of the gravity instrument to detect subsurface-density variations which are often a dominant factor in causing plumb-line deflections.

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(Manuscript received January 7, 1949; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 23, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

A SELECTIVE RELAY AMPLIFIER FOR RECORDING WWV TIME SIGNALS

Edward F. Carome and Harry C. Nash

Abstract—A selective relay amplifier for recording the WWV time signals is described. It is made selective for the 440 cycle note of the WWV signal and thus makes possible the accurate recording of the breaks in the 440 cycle note which come at specified minutes.

Most seismological observatories in the United States receive their automatic time signals from the Navy station, NSS, which broadcasts on several frequencies, one of the most popular of which is 9425 kc, every even hour, GMT. Certain disadvantages in the use of this signal, notably the fact that it is not continuous, have led the staff of the John Carroll Seismological Observatory to design a selective relay amplifier which operates off the WWV time signals. These signals consist of a continuous 440 cycle audio note interrupted for one minute before the hour and each five minutes thereafter. A one-second pulse on every second except the fifty-ninth is broadcast continuously. Both signals are carried on frequencies of 2.5, 5, 10, 15, 20, 25, and 30 megacycles.

The amplifier designed at John Carroll University discriminates against all audio signals except the 440 cycles. The design of this amplifier is an adaptation of the circuit described by HANCHETT [1948]. This circuit employs a twin "T" resistance-capacitance bridge. It tends to reduce the amplitude of all frequencies except 440 cycles, to which it is tuned. Thus the one-second pulses, static, and background noises will not affect the action of the relay. This reducing of spurious pulses eliminates one of the greatest disadvantages of a radio-controlled time signal relay.

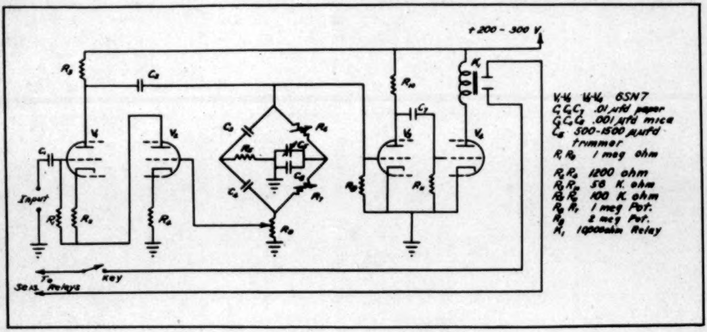

Fig. 1--Schematic circuit diagram

Figure 1 is a schematic circuit diagram of the selective relay amplifier. The input from the radio receiver is applied to the grid of V_1, one-half of a 6SN7, while to the cathode of this same triode is coupled the output of the twin-"T" network. Under these conditions, V_1 has practically no gain at any frequency other than 440 cycles.

In the bridge network the two resistance arms, R_6 and R_7, are made variable in order that the circuit may more easily be tuned. C_5, an adjustable mica trimmer is used for this same reason. The other condensers in the network should also be of the mica type.

The second tube of this amplifier is also a 6SN7. One triode is used as an amplifier while the relay is placed in the plate circuit of the other. Under these conditions, the relay is deenergized and the contacts are closed when the 440 cycle note is being received. The contacts open when the signal ceases.

The relay of the seismograph drum which deflects the light spot is connected in the conventional manner to a telegrapher's key. This key is in series with the relay contacts of the selective relay amplifier. To deflect the light spot automatically, the operator leaves the key open during the minute when the tone is off and closes the key about ten seconds before the resumption of the tone. When the tone is resumed exactly on the fifth minute, the circuit is closed by the selective relay. The light spot remains deflected on the record until the operator opens the key. To deflect the light spot manually, the operator simply closes the key when he hears the one-second pulse resumed at the beginning of a minute.

This system offers the following advantages: maximum freedom from spurious time signals due to background noises and static, both manual and automatic control, and the possibility of obtaining the signal whenever desired.

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(Communicated manuscript received November 24, 1948;
open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

AIR WEATHER SERVICE SFERICS OPERATIONS IN THE CARIBBEAN AREA

Howard F. Willey

Abstract--A general description of the Air Weather Service sferics network in the Caribbean area is given. Operating principles and reasons for a four-station network are described. A discussion of general correlations of sferics with weather conditions is given. Finally the trend of development is summarized.

"Sferics" is the United States and British term for observations or reports of observations of atmospheric electrical discharges. These discharges are often referred to as atmospherics, and it is from this word that the last part is taken and corrupted to sferics. This is further abbreviated for coded message transmissions, to the five-letter group "seric".

Sferics observations in their present form are of chief interest to meteorologists, as they serve to locate the lightning of thunderstorm areas and consequently locate the associated areas of convective activity.

It has been known for many years that electrical energy is radiated from lightning and other atmospheric electrical discharges, and that radio direction finding principles can be used to locate the source of the discharge. The Air Force sferics observations are made by a group of four observing stations arranged at the corners of a quadrilateral. The sferics network now operating in the Caribbean area has stations at Robins Air Force Base, Georgia; Kindley Field, Bermuda; Coolidge Field, Antigua; and Vernam Field, Jamaica. This covers an area, approximately square, with about 1000 mi on each side. The field of observation extends for at least another 1000 mi around the square, except as land masses intervene. Sferics observations with the present equipment are restricted in range over continental areas, and are most successful over ocean areas. This is a very workable situation, as the greatest need for reports is from the ocean areas, which are not covered by any other means except scattered island and ship reports, and in some areas by aerial weather reconnaissance.

The present sferics equipment consists of two loop antennas mounted at right angles to each other and oriented in north-south and east-west planes. As the electrical energy from a sferics discharge arrives at the loops it induces a voltage in each loop that is directly proportional to the cosine of the angle between the plane of the loop and the direction of origin of the electrical wave. For example, a wave coming from the north or south induces maximum voltage in the north-south loop and zero voltage in the east-west loop, while a wave coming from the northeast or southwest induces an equal voltage in each loop. It is thus possible to pass the voltage received from each loop through separate, but exactly matched amplifiers, and then to apply each signal to one pair of the two sets of deflecting plates in a cathode ray tube. The electron beam of the cathode ray tube will be deflected to an angle which corresponds to the angle of origin of the wave. The energy received from lightning is an alternating wave, and therefore causes the electron beam of the cathode tube to oscillate, and to trace a line across the face of the tube. The tube face is calibrated in degrees of azimuth, and as the tube used is of the persistent type, a short interval of time is available in which the angle of the trace may be read.

Electrical waves from lightning are generally in the form of damped waves and are often complex. However, the strongest frequency is around ten kilocycles, and it is to this frequency that the observing equipment is tuned.

During an observation all of the four stations are in communcation with each other by radio. One station controls the observing and synchronizing of the sferics. An observer at the control station visually observes the face of the cathode ray tube and selects a limited number of the many signals that appear. When a strong and distinct signal is seen, the observer presses a continuous wave radio key and sends a radio signal to the other stations. Observers at these stations have also been watching the scopes of their direction finders, and upon hearing the radio signal they read the angle of the sferics signal that is just fading from the scope. These angles are expressed in degrees and represent azimuths to the sferics source.

One hundred and twenty attempts are made to observe sferics during each three-hourly observation, after which a frequency count is made by ten degree sectors of the calibrated scope face to determine the rate of occurence of sferics in each sector. All of the data is transmitted by radio to the control station for plotting.

As electrical waves travel over the Earth on great circle paths, it is possible to use a plotting chart having a gnomonic projection and by extending the azimuths from each station as straight lines, the point of origin of the sferics can be located. Although all azimuths are bi-directional, a brief inspection of the four azimuths will determine the direction in which they will intersect. Each point of intersection is marked on the chart and an intensity is ascribed to it in accordance with the rate of sferics activity observed in the frequency count.

Very rigid rules are enforced throughout the plotting and evaluation procedure to eliminate as far as possible all uncertainties and errors. A relatively small portion of the observed sferics are finally coded and transmitted. Errors arise from several factors such as the inherent design faults of the direction finder, faulty synchronization and the every present human error in following procedures for observing. The selection criteria through which all data must pass is designed to eliminate nearly all errors and to bring the location of the reported sferics within accuracy limits of 25 to 100 mi. When the scale of even our largest synoptic charts is considered, it is apparent that an error of location of even 100 mi over an ocean is not significant in dealing with storm areas.

Sferics networks are made up of four stations for several reasons. It is true that a point can be located by the intersection of two lines or azimuths as observed by only two stations. However, the present direction finder is bi-directional and a third station is desirable to avoid uncertainty and the chance intersections that can be obtained by selecting any two azimuths. The paths of the electrical waves are great circles and the azimuths intersect at antipodal points. However, the probability of receiving and finding the direction of a wave from the other side of the Earth is very small.

It can be demonstrated by geometry that the greatest probable accuracy of the position of a point located by two azimuths is obtained when the interior angle of intersection of the azimuths is 90 degrees. As this angle becomes greater or smaller the probable error of location increases. If a series of 90-degree intersections are plotted about the base line between two sferics stations, the successive points will establish an arc between the stations, and sferics locations made along this arc are the most accurate. This means that accurate fixes at the greatest distances from the stations are obtained when sferics occur at points perpendicular to the central portion of the base line between the stations.

In addition to removing the chance intersections and the ambiguous situations when an intersection falls on the base line, a third station increases the possible base lines from one to three, and thus enlarges the areas in which locations of high probable accuracy can be made. The addition of a fourth station increases the possible base lines to six and also increases the probability of having three stations obtain accurate fixes on the sferics.

The optimum length of base line or distance between stations with the present sferics equipment is about 1000 mi. If we assume a possible error of two degrees in direction finding, the 1000-mi base line will give us an adequate range of observing coverage with location errors in the order of 25 to 100 mi. Shorter base lines reduce the area of accurate coverage and longer ones increase the probable error of location. The present sferics network in the Caribbean is very nearly on 1000 mi base lines.

Sferics networks in the Air Force came into being during the last year of the war and were in operation for only a few months when the rapid demobilization of the Army compelled their abandonment. The experience gained in these sferics networks, although not conclusive, was very encouraging. The value of sferics reports from ocean areas was clearly indicated, and several patterns of the relation of sferics to fronts and waves began to appear. Limited operations were resumed in a relocated Caribbean sferics network in 1947 and are now reaching a satisfactory level.

Two main types of sferics distributions are common. A line of sferics is an indication of the presence of a wave or front. The sferics over the western Atlantic are generally located in advance of cold fronts and may appear as far as 400 mi ahead. In the central and eastern Atlantic, they are characteristically found along and behind the cold fronts. In come cases of frontolysis the sferics appear along the line of the front. An area of sferics is an indication of widespread convection, which in favorable conditions, such as the Gulf of Mexico, may develop into a cyclone.

Forecasters in the Caribbean area are finding sferics to be valuable in locating thunderstorm areas which may lie across air routes and whose presence cannot be detected by other means.

In the analysis of hemisphere charts as made by the Master Analysis Central of the Air Weather Service in Washington, the sferics serve as a valuable aid in confirming the location of fronts over ocean areas, and have been found to fit in very well with the limited number of ship and island reports.

The current year is expected to bring a considerable advance in our knowledge of how to correlate sferics reports with synoptic situations. Several studies are now in progress and will be extended throughout the year. The Air Weather Service is now confident that when a sferics report says that sferics are occurring in a certain area, that almost complete dependence may be placed on the report. However, it must be remembered that the present sferics observing program is only a sampling process at three-hour intervals, and does not yield a complete coverage. Lack of reports from specific areas must not be construed as a report of the absence of thunderstorms in the area, although the odds are favorable that any activity there is not great.

Sferics equipment now under development, is being designed to remove the possible sources of error and some of the limitations of the present equipment. Following the general trend of current development, many automatic features are expected to be incorporated and thus make it possible to make more extensive observations and to remove the requirement for the tedious attention of observing personnel.

Two lines of development in sferics observations are being followed. One is merely the geographical location of sferics, the other is the location and analysis of the wave form of the sferics. It is believed that it may be possible within the next few years to receive an electrical wave from an atmospheric discharge, and by analysis of the shape, strength, and polarization of the wave to determine exactly the type of activity that produced the sferic.

Other investigations of the formation of electrical charges in the atmosphere are very promising and may produce evidence that will alter some of the current meteorological concepts. The development of sferics equipment and the use of various systems in routine observing is being conducted by a number of nations, among whom the British, French, Scandanavians, Swiss, and Japanese are most active.

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(Manuscript received August 3, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

ABSORPTION OF ALPHA RAYS IN THICK SOURCES

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Abstract--The radioactivity of rocks is normally measured by counting the α particles emitted from a powdered sample. The number emitted depends upon the absorption factor of the rock so this must be evaluated before the radioactivity can be accurately known. The various methods of arriving at the absorption factor are discussed and it is suggested that there are errors both in the values proposed by Nogami and Hurley and also in that formerly used in the laboratory of the University of Toronto. Mention is made of the further work that is required in order to arrive at an accurate value.

Introduction--The radioactivity of rocks may be estimated by counting the α particles emitted from a powdered sample. The number of particles counted depends not only on the amount of U and Th and their products present, but also on the thickness of the layer from which the α particles can reach the surface and be counted. This thickness depends on the absorption factor of the rock.

The purpose of this paper is to estimate the error involved when this factor is calculated for rock-forming minerals by means of the Bragg-Kleeman rule. An attempt is made also to arrive at an average absorption factor for common rocks to avoid the necessity of chemical analyses.

It is well known that the relative stopping power of a substance is not constant but is a function of the energy of the α particle. The atomic stopping power increases with increasing range if the atomic number of the absorbing substance is greater than the mean atomic number of air, and decreases with increasing range if the atomic number is less than that of air. Therefore any absorption factor must be an average over all the α-particle energies of the natural α emitters.

Emission from a thick source--The emission per sec/cm^2 of surface of an homogeneous thick source, due to UI alone [NOGAMI and HURLEY, 1948], is

$$N\mu(R_{UI} - r)/4$$

where N is the number of UI atoms disintegrating per sec per cm^3, R_{UI} is the range of UI α particles in air, r is the minimum residual air range necessary for detection, and μ is the range in the mineral divided by the range in air.

The emission per sec/cm^2 is then given by

$$e_{UI} = 10^3 \times 3.08 \times \mu\rho \,\mathrm{UI}\,(R_{UI} - r) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where ρ is the density of the material and UI is the amount of UI in the mineral in gm/gm.

For the UI series in equilibrium

$$E_{UI} = \Sigma_{UI}\, \mu\rho \times 10^3 \times 3.08 \,\mathrm{UI}\,(R - r) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where μ must be kept under the summation sign, contrary to the procedure adopted by Nogami and Hurley.

Similarly for the thorium series

$$E_{TH} = \Sigma_{TH}\, \mu\rho \times 10^3 \times 1.03 \,\mathrm{Th}\,(R - r)$$

And for the AcU series, using the value 0.046 as the ratio of the activity of AcU to UI

$$E_{AcU} = \Sigma_{AcU}\, \mu\rho \times 10^3 \times 0.14 \,\mathrm{UI}\,(R - r)$$

It is convenient, however, to determine an average value of $\mu\rho$ and in this way put it in front of the summation sign; $\mu\rho$ will then be characteristic of the absorbing substance.

Using this average value we can then employ (1).

$$E = \mu\rho \times 10^3 \text{ (89.41 UI + 26.60 Th) alphas/sec/cm}^2$$

for the total emission.

Determination of $\mu\rho$ for mica--In order to determine this average value it is necessary to know the range-energy relation for α particles in the mineral. This has been done by BRIGGS [1927] for mica, using α particles from RaC$'$. By smoothing, interpolating, and slightly extrapolating his results, the data given in Table 1 have been obtained. It will be seen that $\mu\rho$ varies from 1.38 to 1.94 $\times 10^{-3}$ for the α particles concerned. It is this variability that makes (2) with $\mu\rho$ outside the summation incorrect.

Table 1--Velocities and ranges of α particles and values of $\mu\rho$ obtained from Briggs values

Element	Velocity	Range in mica	Range in air	$\mu\rho$
	cm/sec	mg/cm^2	cm	gm/cm^3
UI	1.420×10^9	5.15	2.65	1.94×10^{-3}
UII	1.511×10^9	5.50	3.21	1.71×10^{-3}
Io	1.498×10^9	5.40	3.15	1.71×10^{-3}
Ra	1.519×10^9	5.60	3.29	1.70×10^{-3}
Rn	1.625×10^9	6.65	4.04	1.65×10^{-3}
RaA	1.699×10^9	7.4	4.64	1.59×10^{-3}
RaC$'$	1.922×10^9	10.4	6.87	1.51×10^{-3}
RaF	1.597×10^9	6.45	3.83	1.68×10^{-3}
AcU	1.511×10^9	5.5	3.24	1.70×10^{-3}
Pa	1.569×10^9	6.1	3.63	1.68×10^{-3}
RdAc	1.701×10^9	7.4	4.66	1.59×10^{-3}
AcX	1.659×10^9	7.0	4.31	1.62×10^{-3}
An	1.812×10^9	8.5	5.68	1.50×10^{-3}
AcA	1.884×10^9	9.4	6.44	1.46×10^{-3}
AcC	1.785×10^9	8.3	5.42	1.53×10^{-3}
Th	1.446×10^9	4.95	2.84	1.75×10^{-3}
RdTh	1.615×10^9	6.6	3.96	1.67×10^{-3}
ThX	1.653×10^9	6.9	4.26	1.62×10^{-3}
Thn	1.739×10^9	7.85	4.99	1.57×10^{-3}
ThA	1.805×10^9	8.45	5.62	1.50×10^{-3}
ThC	1.707×10^9	7.5	4.71	1.59×10^{-3}
ThC$'$	2.054×10^9	11.7	8.53	1.38×10^{-3}

With these results weighted according to the activities, the average value of $\mu\rho$ for all the significant α emitters is 1.66×10^{-3} gm/cm^3 for the mica used here. Using the composition $K_2O\ 3Al_2O_3\ 6SiO_2\ 2H_2O$ given by Briggs the absorption factor calculated by means of the Bragg-Kleeman rule, according to which the atomic stopping power is proportional to the square root of the atomic weight, is 1.50×10^{-3}.

In order to determine the error incurred in using the Bragg-Kleeman rule for other minerals, the absorption factors have been calculated by means of the Bragg-Kleeman rule, according to which the atomic stopping power is proportional to the square root of the atomic weight, is 1.50×10^{-3}.

In order to determine the error incurred in using the Bragg-Kleeman rule for other minerals, the absorption factors have been calculated by another method. Using the values of $\mu\rho$ for each element calculated mostly from values given by CURIE [1935], for α particles from RaC$'$, the absorption factors of various minerals have been determined (see Tables 2 and 3).

Table 2--Ranges of α particles from RaC′ and values of $\mu\rho$ for various substances from Curie's values

Element	Range of RaC′ alphas	$\mu\rho$
	microns	
Li	129.1	0.988×10^{-3}
Mg	57.8	1.45×10^{-3}
Al	40.6	1.57×10^{-3}
Ca	78.8	1.75×10^{-3}
Fe	18.7	2.11×10^{-3}
0	6.54 cm	1.36×10^{-3}
Si	46.3	1.61×10^{-3}
K	148.0	1.84×10^{-3}
H	32.5 cm	0.42×10^{-3}
S	....	1.69×10^{-3}[a]
Pb	24.1	3.93×10^{-3}
Cu	18.3	2.36×10^{-3}

[a] Estimated from atomic number.

This comparison shows that the two methods give the same result for values of $\mu\rho$ from 1.50×10^{-3} to 1.70×10^{-3}. This range includes all the common rock forming minerals.

Since Briggs' results for RaC′ α particles agree with those obtained by both the other methods (1.51, 1.50, 1.50×10^{-3} respectively) it seems reasonable to assume that the Bragg-Kleeman rule give results about ten per cent too low for the common rock-forming minerals. This difference is due to the dependence of stopping power on energy.

It is likely that all the values of $\mu\rho$ obtained by calculation from stopping powers of individual elements will be about ten per cent too low. This should hold roughly for high atomic numbers also. The Bragg-Kleeman rule gives values consistently ten per cent higher than those for the heavier minerals, (in galena the difference is 20 per cent).

Table 3--Comparison of values of $\mu\rho$ for various minerals calculated from Curie's values for RaC′ α particles and by Bragg-Kleeman rule

Mineral	$\mu\rho$ for RaC′ α particles	$\mu\rho$ from Bragg-Kleeman rule
Diopside $Ca\,Mg\,Si_2O_6$	1.53×10^{-3}	1.55×10^{-3}
Pyrite $Fe\,S_2$	1.92×10^{-3}	2.07×10^{-3}
Galena $Pb\,S$	3.68×10^{-3}	4.30×10^{-3}
Hematite Fe_2O_3	1.92×10^{-3}	3.05×10^{-3}
Chalcopyrite $Cu\,Fe\,S_2$	2.08×10^{-3}	2.24×10^{-3}
Biotite $K(Mg.\,Fe)_3\,Al\,Si_3O_{10}\,(OH)_2$	1.70×10^{-3}	1.69×10^{-3}
Magnetite Fe_3O_4	1.93×10^{-3}	2.08×10^{-3}
Quartz SiO_2	1.50×10^{-3}	1.48×10^{-3}
Orthoclase $KAl\,Si_3O_8$	1.54×10^{-3}	1.54×10^{-3}
Mica (Briggs)	1.50×10^{-3}	1.50×10^{-3}

Table 4--Values of $\mu\rho$ for igneous rocks of average composition calculated by Bragg-Kleeman rule

Daly's number	Rock	$\mu\rho$
		gm/cm^3
1	Precambrian granite	1.51×10^{-3}
45	Granodiorite	1.51×10^{-3}
47	Diorite	1.53×10^{-3}
58	Basalt	1.57×10^{-3}
66	Diabase	1.57×10^{-3}
75	Peridotite	1.54×10^{-3}
79	Dunite	1.50×10^{-3}

Therefore, for minerals containging heavier elements it would seem that the Bragg-Kleeman rule give a better approximation than for minerals containing mainly elements of low atomic number.

Estimation of average absorption factor--In order to estimate an absorption factor applicable to most common rocks, a selection of the commonest igneous rocks was made from the list given by DALY [1933]. Using his average compositions the values of $\mu\rho$ were calculated using the Bragg-Kleeman rule. These appear in Table 4.

These values range from 1.50 to 1.57×10^{-3} with the mean at 1.53×10^{-3}. Assuming this result ten per cent too low gives, as an average absorption factor for common igneous rocks, the value 1.69×10^{-3} gm/cm^3.

This result is higher than that now in use in this laboratory, the value used here being 1.45×10^{-3}. On this basis, all the values of $\mu\rho$ should be raised an average of 17 per cent, the correction varying from 15 to 19 per cent for individual rocks.

The results used by NOGAMI and HURLEY [1948] in their Figure 2 have been examined by least squares in an attempt to detect the error discussed above. No significant error was found. Most of Nogami and Hurley's results are for magnetite and it is very desirable that similar work be done on igneous rocks.

In conclusion, I desire to thank E. C. Bullard and J. Tuzo Wilson for much helpful advice. I am indebted to P. M. Hurley for supplying the data on which his Figure 2 was based.

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(Communicated manuscript received December 8, 1948;
open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

THE PREDICTION OF LONGSHORE CURRENTS

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(Contribution from the Scripps Institution of Oceanography, New Series, No. 422,
and Fluid Mechanics Laboratory Publication No. He-116-279)

Abstract--Longshore currents are an important factor in beach erosion. A relationship is derived from theoretical considerations between the velocity of the longshore current and the height and period of the breaking waves, the angle between the breakers and the beach contours (assumed straight and parallel), and the beach slope in the breaker zone. Field observations and laboratory experiments support this relationship.

Introduction

Waves breaking at an angle with the shoreline set up a longshore current, or littoral current, which may reach a velocity of several knots, and which is capable of carrying large amounts of sediment. If the flow of sediments is impeded, either by direct obstructions in the path of the longshore current, or by interfering with the waves that maintain the current, the equilibrium of the beaches is disturbed, and silting or eroding will follow. A knowledge of the relationship between the character of the ocean waves and the direction and magnitude of the longshore current has proven helpful in the design of jetties and breakwaters.

The impetus for this study came, however, from a different source. During the War, considerable difficulty was experienced in landing amphibious craft in the presence of a longshore current. At times the magnitude of this current was sufficient to cause a landing vehicle to broach, even though it had successfully negotiated the breakers. Often this represented a greater hazard than that afforded by the breaking waves, and it was attempted, therefore, to include a forecast of the longshore currents among the forecast of other characteristics of the surf zone [SVERDRUP and MUNK, 1946].

Field and laboratory observations

Observations of longshore currents were initiated along the beach at Oceanside, California, and simultaneously in the Fluid Mechanics Laboratory of the Department of Engineering at the University of California, Berkeley, California. The results from these studies apply only to straight beaches with parallel contours. It has not been possible to evaluate the effect of currents beyond the breakers, nor the effect of irregularities in the shoreline.

Beach observations--The following wave data were collected each day that measurements were made (see Table 1): breaker height H, wave period T, angle of breaking , depth of breaking h, mean beach slope m, and velocity of longshore current V. The angle is difficult to obtain, but it can be measured from a pier by standing directly above the breakers and taking a bearing along the breaking crest. Soundings were taken along the pier, and the position of the breakers noted. This was necessary because the beach did not have a regular slope but was characterized by an outer and inner bar. These bars were constantly shifting position, particularly with heavy surf. The wind speed and direction were recorded when the wind was strong enough to be of importance.

Longshore currents were measured by three different methods. Two of these involved the travel time of a current cross over a known distance. The current cross consisted of a sheet metal cross, suspended from a small float, and held upright by a lead weight (see Fig. 1). The line between the float and the cross could be adjusted to measure the current at any desired depth. The damping effect of the wooden braces shown in Figure 1 held the instrument fairly steady in the surf Two types were used, a large cross 16 inches high and a small cross eight inches high, the latter for measurements in shallow water.

The first method was to take an average of several 100-ft runs. One end of a 100-ft line was attached to the current cross and the other to a block of wood which could be lowered from the pier to the water surface by a short line. The cross was dropped into the current, the block was lowered to the surface and then the time required to draw the 100-ft line taut was measured.

Table 1--Tabulation of field data

No.	Date	Time	H	T	α	m	V
	1945	h m	ft	sec	°		ft/sec
1	Feb. 9	.. ..	5	10	15	0.016	2.5
2	Feb. 21	.. ..	5.5	9	12	0.02	2.2
3	Feb. 24	.. ..	7	9	15	0.023	3.0
4	Mar. 5	.. ..	6	7	7.5	0.017	1.8
5	Mar. 14	10 15	5	10	10	0.031	3.6
6	Mar. 14	13 30	8	10	10	0.022	2.8
7	Mar. 14	14 30	8	10	10	0.023	2.3
8	Mar. 16	10 40	6.5	12	10	0.02	2.4
9	Mar. 16	13 50	4.5	12	10	0.02	2.4
10	Mar. 16	14 45	4.5	12	10	0.019	2.7
11	Mar. 16	15 10	4.5	12	10	0.019	2.1
12	Mar. 22	.. ..	6.5	15	5	0.016	1.7
13	Mar. 23	.. ..	8	7	17.5	0.022	5.2[a]
14	Mar. 24	10 00	5	8	10	0.03	3.3
15	Mar. 24	10 30	8.5	8	12	0.02	2.5
16	Mar. 27	.. ..	5	15	5	0.026	2.4
17	Apr. 9	09 45	9	8	15	0.019	5.5[a]
18	Apr. 9	11 00	9	8	15	0.019	3.9

[a]Following 22 knot wind blowing within 22° of parallel to coast.

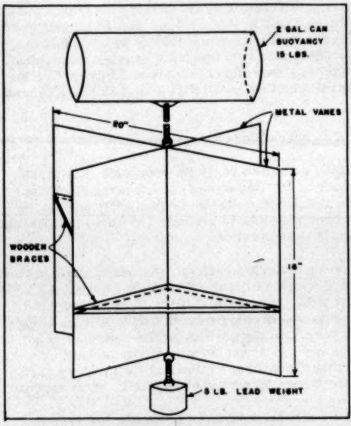

Fig. 1--Current cross used for field measurements of longshore currents

The second method was to drop the cross into the current, either from a boat or from the pier, and to permit it to drift freely. Observers followed along the shore and recorded the time when the cross passed markers at 100-ft intervals until the cross was washed up on the beach, or had drifted out to sea. This method permitted the measurement of currents over long stretches and minimized the effect of errors in timing.

A third method was tried along the beach a few miles north of Oceanside. Fluorescein dye markers were dropped into the current from a low-flying blimp, and were photographed from a plane at five-minute intervals. A party on the beach recorded the wave height and period. On the photographs the progress of the dye could be measured from landmarks along the beach, and the velocity computed. This method has the advantage that breaker angles may be measured directly. However, the diffusion of the dye makes it difficult to determine the exact point of advance. Furthermore, the combination of good flying weather and good waves was so rare that it was more satisfactory to use the other methods.

The surf at Oceanside was usually characterized by a zone of higher breakers on the outer bar, and a zone of lower breakers on the inner bar (see Fig. 2). On days where the majority of waves were breaking on the outer bar, the current was almost constant from the outer line of breakers to shore. During spring tides, however, when only a few of the highest waves were breaking on the outer bar, there would be a weak current between the two lines of breakers, and a strong current between the inner line of breakers and shore. At all times the current was small or negligible beyond the outer breaker.

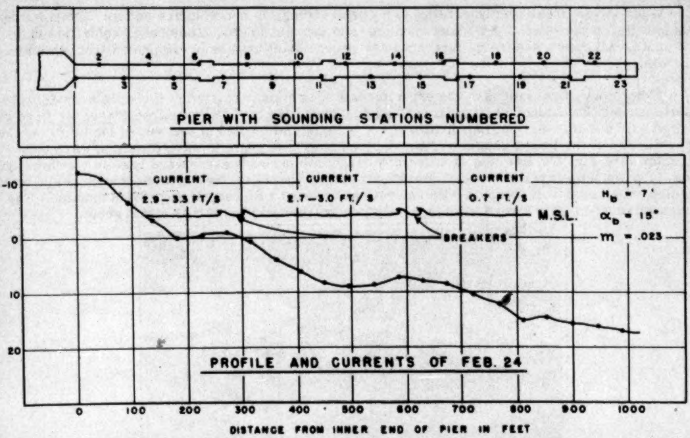

Fig. 2--Typical arrangements for field observations at Oceanside

Along any given stretch of beach the velocity varied as much as 25 per cent either way from the mean value. The observed variations are similar in duration (three to five minutes) to the surges that are observed in rip currents, and are probably associated with the variations in wave height over similar time intervals. Consequently these variations are variations in time, and not in position. This is clearly borne out by observation from a blimp of the movement of six dye markers at different parts of the Oceanside beach (see Fig. 3). In this figure the velocities of markers (1) and (2) were high between runs 1 and 2, and low between runs 2 and 3 (in the case of marker (1) the velocities were low between runs 2 and 4. The velocities of markers (4), (5), and (6) were high between runs 3 and 4, and low between runs 4 and 5.

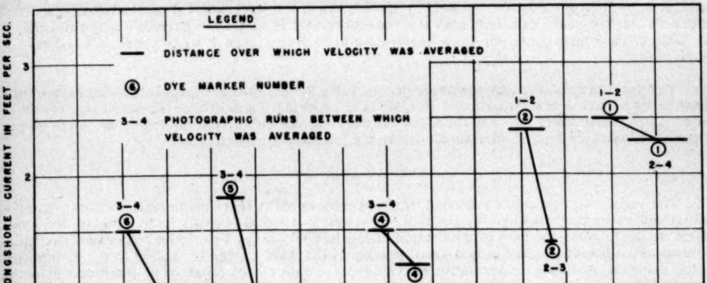

Fig. 3--Movement of dye-markers photographed from a blimp

When waves break nearly parallel to a coast, strong rip currents are set up. These currents run parallel to the beach for a short distance, and then out to sea. They reach velocities up to 1.5 knots. All cases where rip currents were predominant have been eliminated from this investigation.

Laboratory observations--The experimental equipment consisted of a concrete wave basin approximately 58 ft long, 39 ft wide, and two feet deep. Waves of any desired frequency were generated with a motor-driven flap, hinged at the bottom, and located at one end of the tank. At the opposite end of the basin, beaches of any desired slope and angle to wave direction were constructed (see Fig. 4). Beaches of three different absolute roughnesses were used in the investigation. The smoothest beaches were covered with metal sheets or very smooth neat cement. Intermediate roughness was obtained with natural sand bonded with cement to prevent erosion. The roughest beaches were coated with 1/4-inch pea gravel and bonded with a thin grout.

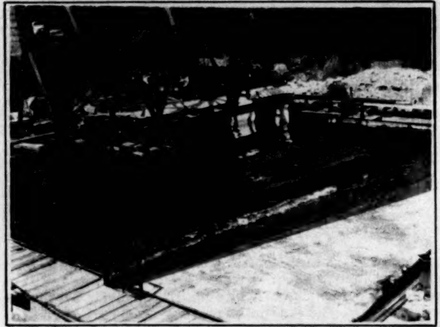

Fig. 4--Laboratory wave basin

Wave heights, breaker heights, and the depth of breaking were measured with electric point gages. Wave periods were obtained by observing the frequency of the wave-generation flap. The angle of the breakers was measured from vertical photographs. The longshore current was measured by timing the travel of KM_nO_4 dye over each five-foot interval marked along the beach. A careful review of the data indicated that measurements of longshore current along different sections of the central position of the beach (five to 15 ft in Figure 4) were consistent and reproducible.

The experimental results are presented in Table 2. All values represent the average of at least three separate determinations. For all runs reported, the length of the beach was ten or more times the width of the surf zone, and all waves broke well inside the toe of the beach slope. Figure 5 illustrates typical surf conditions in the laboratory experiments.

Analysis of the data

The longshore current is a stream which receives energy from the breaking waves. Equilibrium conditions prevail when the fraction of the energy received (available to maintain the longshore motion) equals the rate of dissipation of mechanical energy by friction. An exact analysis is rendered difficult because only a small portion of the wave energy is applied to the maintenance of the current. Although a correlation of the observed data can be obtained by intuitive reasoning based on kinematical considerations or by dimensional analysis, it is believed that relations derived from mechanical principles will yield a better understanding of the phenomenon and also provide a better basis for forecasting longshore currents. Accordingly, two approaches are presented; one based on energy balance, and the other on momentum considerations, both assuming that waves have been breaking long enough to set up a steady state, and that the beach is straight, and the bottom slope uniform.

Energy approach--Consider a volume of water ABCDE (see Fig. 6) extending between shore and the breaking waves, from the surface to the bottom. Over a width of beach dx the total wave energy entering the volume ABCDE equals $C\,E\cos\alpha\,dx$, where C is the wave velocity (almost equal to the

Table 2--Tabulation of laboratory data and results

No.	Aver. K	Slope m	Breaker conditions					Longshore velocity V	
			T	H	h	α	$(mH^2/T) \sin 2\alpha$	Calc.	Obs.
			sec	ft	ft	°		ft/sec	ft/sec
1	0.0397	0.066	1.00	0.47	0.75	18.3	0.205	1.21	0.78
2	0.0397	0.066	1.06	0.32	0.44	13.8	0.143	0.74	0.64
3	0.0397	0.066	1.14	0.40	0.56	14.6	0.166	0.87	0.82
4	0.0397	0.066	1.15	0.31	0.41	12.6	0.133	0.66	0.68
5	0.0397	0.066	1.25	0.30	0.39	11.7	0.124	0.59	0.76
6	0.0397	0.066	1.32	0.32	0.40	11.7	0.127	0.61	0.75
7	0.0397	0.066	1.40	0.29	0.37	10.9	0.114	0.54	0.64
8	0.0397	0.144	1.90	0.16	0.24	17.6	0.104	0.58	0.75
9	0.0397	0.144	2.13	0.15	0.23	17.2	0.095	0.55	0.66
10	0.0397	0.144	2.22	0.15	0.24	17.3	0.094	0.55	0.50
11	0.0397	0.241	0.72	0.28	0.48	18.2	0.250	1.27	1.33
12	0.0397	0.241	0.92	0.35	0.52	16.5	0.260	1.24	1.27
13	0.0397	0.241	1.14	0.22	0.28	10.4	0.154	0.60	0.53
14	0.0397	0.241	1.22	0.22	0.27	10.6	0.151	0.60	0.69
15	0.0070	0.100	0.99	0.24	0.32	28.0	0.169	1.65	1.68
16	0.0070	0.100	1.32	0.22	0.27	22.8	0.138	1.20	1.45
17	0.0070	0.100	1.63	0.16	0.23	18.8	0.099	0.96	0.96
18	0.0070	0.100	1.98	0.16	0.22	18.4	0.092	0.85	0.76
19	0.0070	0.139	0.83	0.28	0.43	56.6	0.234	3.03	2.46
20	0.0070	0.139	0.91	0.23	0.33	45.3	0.201	2.35	2.31
21	0.0070	0.139	1.00	0.22	0.29	38.8	0.187	2.06	2.22
22	0.0070	0.139	1.12	0.20	0.24	33.2	0.166	1.69	1.93
23	0.0070	0.139	1.35	0.20	0.25	31.1	0.154	1.58	1.52
24	0.0070	0.260	0.80	0.34	0.62	57.5	0.324	3.97	3.78
25	0.0070	0.260	0.90	0.29	0.43	52.5	0.286	3.26	3.34
26	0.0070	0.260	0.98	0.28	0.41	47.2	0.275	2.99	3.00
27	0.0070	0.260	1.23	0.20	0.26	32.5	0.197	1.82	1.91
28	0.0070	0.260	1.27	0.22	0.23	31.9	0.207	1.78	1.76
29	0.385	0.098	0.95	0.26	0.36	30.1	0.182	0.52	1.03
30	0.385	0.098	1.33	0.21	0.27	21.4	0.130	0.31	0.46
31	0.385	0.098	1.67	0.16	0.20	18.0	0.096	0.22	0.20
32	0.385	0.098	1.99	0.12	0.19	16.4	0.072	0.17	0.15
33	0.385	0.143	1.08	0.33	0.47	30.4	0.232	0.69	1.32
34	0.385	0.143	1.36	0.29	0.38	24.6	0.188	0.52	0.63
35	0.385	0.143	1.58	0.20	0.27	19.3	0.131	0.33	0.36
36	0.385	0.143	1.91	0.20	0.26	18.4	0.121	0.30	0.32
37	0.385	0.143	2.32	0.22	0.30	19.1	0.122	0.30	0.18

1-14 (Lab. 1), natural-sand beach; 15-28 (Lab. 2), beach covered with sheet metal or smooth cement; 29-37 (Lab. 3), beach covered with 1/4-inch pea gravel.

group velocity for breaking waves), E is the mean energy per unit surface area of the breaking waves, and α is the angle formed between the breaking crest and the shoreline. Of the energy that advances parallel to shore (C E cos αdx) sin α, a small fraction s is responsible for setting up longshore currents. The greater part of the wave energy entering this volume is destroyed in the breaker and turned into heat, or may be responsible for piling water against the shore and setting up rip currents.

Energy is dissipated in a layer of frictional resistance along the bottom. The frictional force per unit width of beach equals

$$k \rho V^2 \ell' dx \quad \text{.........................} \quad (1)$$

and the rate at which energy is dissipated in the volume ABCDE equals

$$k\rho V^3 \ell' dx \quad \text{.......} \quad (2)$$

where k is a friction parameter depending on the hydraulic roughness of the bottom, V the velocity of the longshore current, and ℓ' the distance along the bottom from shore to breaker line. With good approximation $\ell' = \ell$ (see Fig. 6). If m denotes the average beach slope, and h the depth at which the waves break, then

$$m = h/\ell \quad \text{.......} \quad (3)$$

Assuming a steady state, all the energy available for longshore currents entering the volume ABCDE due to wave action must equal the loss of energy due to friction

$$sCE \cos \alpha \sin \alpha \, dx = k\rho V^3 \, dx \, h/m \quad \text{.......} \quad (4)$$

The following relationships derived by the solitary wave theory have been found to apply to breaking waves with good approximation [SVERDRUP and MUNK, 1946; MUNK, 1949].

$$E = (\rho g/L)(4h\, H/3)^{3/2} \quad \text{.......} \quad (5)$$

$$C = [g(h + H)]^{1/2} = L/T \quad \text{.......} \quad (6)$$

$$h = 1.28\, H \quad \text{.......} \quad (7)$$

$$Q = 4\, h^2 \sqrt{H/3h} \quad \text{.......} \quad (8)$$

where ρ is the density of water, g the acceleration due to gravity, H, L, and T the height, length, and period of the breaking wave, h the depth of breaking, and, for later reference, Q is the cross-sectional area beneath the profile of a breaking wave crest. Combining (4), (5), (6), and (7) gives

$$V = K\, [(m\, H^2/T) \sin 2\alpha]^{1/3} \quad \text{.......} \quad (9)$$

where

$$K^3 = 0.871\, g\, (s/k) \quad \text{.......} \quad (10)$$

According to (9) the velocity of the longshore current depends upon the breaker height, the wave period, the angle formed by the breakers, the beach slope, and the hydraulic roughness of the beach. The first three parameters can be predicted from weather maps [SVERDRUP and MUNK, 1946]; the latter two remain relatively constant over a given beach.

The above solution applies to a situation in which the waves have been breaking long enough to set up a steady state, and in which the region chosen is far enough from any obstruction on the beach so that a full-strength current is reached. A more general solution has been derived which is not subject to these limitations. From these solutions numerical values have been computed for the duration of the transient state, and for the distance from a breakwater or discontinuity in the beach over which a current must flow to reach its full velocity. Both these values are surprisingly small. A current will build up to an essentially steady state within five minutes of the time a train of waves starts to break on a beach, and will have practically its full value within 200 yards of a breakwater or other obstruction. The short duration time is consistent with observations of three to five minute variations in longshore currents due to the variation of wave height over similar time intervals (see Fig. 3).

Momentum approach--With the breaking of every wave a certain water mass is thrown into motion in the direction of wave propagation. The longshore component of this motion provides the driving force for the longshore current.

Consider again the volume ABCDE (see Fig. 6). Let Q represent the cross-sectional area of a breaking wave crest moving with velocity C, L the length of the breaking wave, α the angle formed by the breaking crest with the shoreline, and ρ the density of water. Then $\rho Q\, C/L$ is the average momentum per unit surface area, and $C\, (\rho Q\, C/L) \cos \alpha dx$ the mean flux of momentum into ABCDE. The component of momentum flux parallel to shore equals

$$C \sin \alpha (\rho Q\, C/L) \cos \alpha dx \quad \text{.......} \quad (11)$$

The broken water is quickly slowed down by turbulent friction to the mean velocity V of the longshore current, and eventually expelled from the surf zone, giving rise to a momentum flux outward of

$$V\, (\rho Q\, C/L) \cos \alpha dx \quad \text{.......} \quad (12)$$

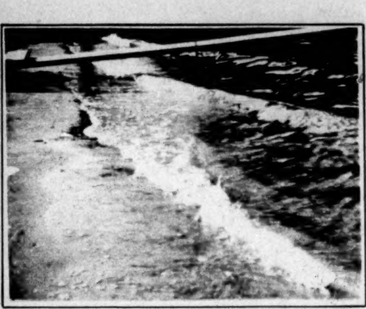

Fig. 5--Surf-zone on smooth laboratory beach

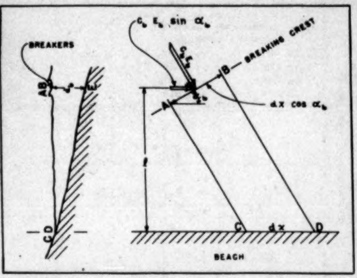

Fig. 6--Schematic diagram for energy and momentum considerations of longshore currents

The difference between (11) and (12)

$$(C \sin\ \alpha - V)(\rho Q\ C/L) \cos \alpha dx \quad \ldots\ldots\ldots\ldots\ldots (13)$$

represents the net flux of momentum, or equivalent force, applied by the breakers upon the water mass in the surf zone.

Since the longshore current is maintained at an essentially constant rate, this force is balanced by frictional force along the bottom (1). Equations (1), (3), (6), and (13) give

$$V^2 = a\ (C \sin\ \alpha - V) \quad \ldots\ldots\ldots\ldots\ldots (14)$$

where

$$a = mQ \cos\ \alpha/khT$$

Solving for V results in

$$V = (a/2)\left[\sqrt{1 + 4C \sin\ (\alpha/a)} - 1\right] \quad \ldots\ldots\ldots\ldots\ldots (15)$$

where according to (6) and (7) $C = (2.28\ gH)^{1/2}$. Substituting for Q from (8) and using (7) leads to

$$a = (2.61\ mH \cos\ \alpha)/(kT) \quad \ldots\ldots\ldots\ldots\ldots (16)$$

where, according to (14)

$$k = (2.61\ mH \cos \alpha)(C \sin\ \alpha - V)/TV^2 \quad \ldots\ldots\ldots\ldots\ldots (17)$$

Equation (15) gives the velocity of the longshore current as a function of the same variables that appeared in (9), and the solution is subject to the same limitations that were discussed when dealing with the energy approach.

Comparison of theory with observed data

In Figure 7 the observed longshore currents are plotted against the wave characteristics as they appear on the right side of (9). Average values of the friction parameter k were determined by substitution of the observed data in (17) for the various types of beach surface investigated. Except for the roughest beach, it was possible to draw a straight line through each set of data, the slope of which is the proportionality constant K of (9). Table 3 illustrates the order of magnitude of the energy fractions available for maintenance of longshore currents, as obtained from (10).

The beach at Oceanside and the natural-sand beach in the laboratory (Lab. 1) have values of s that are comparable. The sand-surface textures of these two beaches were comparable, but the values of the friction parameter k differ by five-fold. A part of this difference may be ascribed to the fact that the beach at Oceanside possessed bars whereas the laboratory beach was a plane,

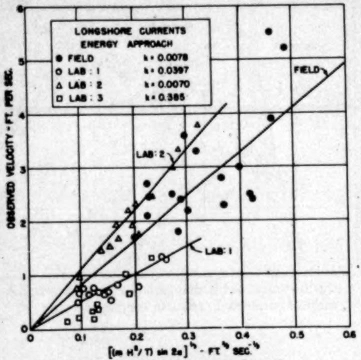

Fig. 7--Longshore currents based on energy approach

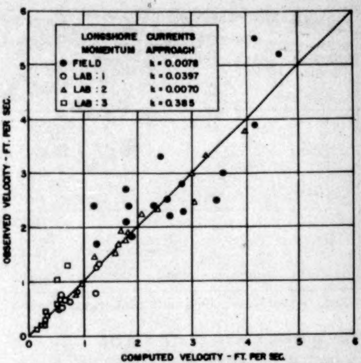

Fig. 8--Comparison between observed and calculated velocities of longshore currents based on momentum approach

Table 3--Values of parameters for field and laboratory data

Beach	k	K	s
Field	0.0078	8.2	0.15
Lab 1	0.0397	5.12	0.19
Lab 2	0.0070	11.02	0.33
Lab 3	0.385	....	...

undisturbed surface. However, k depends upon the hydraulic roughness of the beach rather than the absolute roughness of the beach surface. The experiments with the Lab 1 beach were characterized by relatively weak longshore velocities so that viscous forces were relatively large. Thus the higher values of k might be ascribed to boundary layer resistance in contrast to resistance governed solely by roughness. On the other hand, the Lab 2 beach (sheet metal or smooth concrete) was the smoothest one investigated and the values of k are correspondingly small. However, the longshore velocities were in general larger even than those encountered at Oceanside so that it offered less resistance to flow and was therefore able to absorb a larger fraction of the available energy as indicated by the large value of s.

The scatter of the data shown in Figure 7 results primarily from the difficulty of measuring the breaker angle α, both in the laboratory and the field. The very rough beach (Lab 3, 1/4-inch pea gravel) showed a particularly wide range in the individual values of k, from 0.07 to 1.2, and these depended in a systematic fashion upon the longshore velocity. In this case the theory cannot assume a constant average value of k.

Figure 8 shows the observed longshore current plotted against values of the current computed according to (15) using the above average values of k. The agreement of these results indicates that the theory employed is essentially correct.

Conclusion

The laboratory investigation corroborates the field data and the theory, but indicates the need for systematic work, such as has been done in the case of pipe flow, in order to correlate the friction parameter with measureable beach and wave characteristics. Meanwhile, reasonable computations of longshore currents may be obtained by using either (9) or (15) with a value of k taken equal to that obtained from the Oceanside data. Equation (15) has the advantage that no assumption has to be made regarding the selection of the energy fraction available.

The relationships derived here may find application in two ways: (a) in the prediction of longshore currents on the basis of the predicted values for the height, period, and direction of the breaking waves; (b) in the computation of the seasonal variations in the magnitude and direction of longshore currents at chosen localities, on the basis of climatological wave data [**BURT and SAUR, 1948**]. The restriction to straight beaches with uniform bottom topography greatly limits the usefulness of these applications.

Acknowledgments--This work represents results of research carried out for the Office of Naval Research, the Hydrographic Office, and the Bureau of Ships of the Navy Department under contract with the University of California. We are indebted to Ralph E. Jentoft, Jr. for his assistance in carrying out the observations while on wartime duty at the Scripps Institution.

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(Manuscript received May 24, 1948; presented at the Pacific Coast Meeting, Berkeley, California, February 14, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

DEPTH OF MOTIONLESS LAYER AS INFERRED FROM THE DISTRIBUTION OF SALINITY IN THE OCEAN

Koji Hidaka

Abstract--Using the distribution of salinity in the Atlantic as given by the Meteor data, the depth of no motion was computed from the equation for the diffusion of salt, assuming the preponderance either of vertical or of horizontal mixing. Assuming horizontal mixing, no motionless layer could be detected; but assuming vertical mixing, the depth of no motion fell between 900 and 1400 m over most of the Atlantic between 40°S and 20°N.

In the dynamical estimation of ocean currents propounded by V. Bjerknes and W. Sandström, we can only know the difference in current velocity between two layers placed at different levels, and the absolute velocity in either of these two layers is impossible to determine unless the velocity in the other layer is known. Up to the present it has been customary to choose the lower layer at a level sufficiently deep for the motion of water to be assumed almost insensible, and thus to obtain an approximate velocity in the upper layer.

The above method is, of course, applicable as a rough approximation. But in the light of modern oceanographical observations, the assumption that the motion of water is very slow in deeper layers is by no means correct. For this reason, several attempts have recently been made to detect the motionless layers in the ocean from various points of view.

The author has long cherished the idea that it might be possible to find the depths of the motionless layers from the distribution of salinity, assuming that the actual distribution of salinity is the result of diffusion of salts in the water. This paper deals with the results of numerical computation based upon this assumption.

The differential equation governing the distribution of salinity S in sea water is

$$\partial S/\partial t + u\partial S/\partial x + v\partial S/\partial y + w\partial S/\partial Z = k_1\partial^2 S/\partial x^2 + k_2\partial^2 S/\partial y^2 + k_3\partial^2 S/\partial z^2 \quad \ldots (1)$$

where t is the time, u, v, and w are the components of current velocity in directions of the x-, y-, and z-axes, and k_1, k_2, and k_3 the coefficients of diffusion in the x, y, and z directions. Supposing the motion to be stationary, we have, since $u = v = w = 0$ in a motionless layer

$$k_1\,\partial^2 S/\partial x^2 + k_2\partial^2 S/\partial y^2 + k_3\partial^2 S/\partial z^2 = 0 \quad \ldots\ldots\ldots\ldots\ldots (2)$$

A solution of this equation can be expected to give the levels of motionless layers.

Now since the two first terms in the left-hand member in (2) represent the horizontal mixing, we may put $k_1 = k_2$. The third term, representing vertical mixing, is in general equal neither to k_1 nor k_2. Hence (2) will be transformed into

$$k_1(\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2) + k_3\partial^2 S/\partial z^2 = 0 \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where $k_1 \neq k_3$.

Moreover, we may imagine that the horizontal mixing will seldom take place with the same degree of intensity as the vertical, and therefore usually one of the two terms in (3) alone will predominate.

On this supposition, if the horizontal mixing predominates, the motionless layer is given by

$$\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

and by

$$\partial^2 S/\partial z^2 = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where the vertical mixing prevails.

Numerical computations based on these principles were carried out on the salinity data of the 1925-1927 Meteor expedition in the Atlantic Ocean [BOEHNECKE and OTHERS, 1932].

Assuming horizontal mixing to predominate, we utilized the charts of salinity distribution at 200, 300, 400, 500, 600, 700, 800, and 1000 m (some of them published and available, the others drawn by the author), and the numerical values of $\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2$ were obtained by numerical differentiation of

$$\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2 = (S_e + S_w - 2S_0)/[(\text{length of arc } 1^\circ \text{ lat}) \cos \phi]^2$$
$$+ (S_n + S_s - 2S_0)/\ (\text{length of arc } 1^\circ \text{ lat})^2$$

where ϕ is the latitude, S_0 the salinity at the place for which the value of $\partial^2 S/\partial x^2 + \partial^2 S/\partial y^2$ is sought, S_e and S_w the values of salinity at places distant by one degree longitude to the east and west, respectively, and S_n and S_s those at places distant by one degree latitude to the north and south, respectively. Since we only require the place where this value is zero, we have practically only to compute the values of $(S_e + S_w - 2S_0)/\cos^2 \phi + S_n + S_s - 2S_0$. Plotting the values on a map, and searching for the loci where these quantities vanish, we should have the location of the layers of no motion.

Unfortunately, however, we did not succeed in determining the motionless layers by this method.

We therefore assumed the predominance of vertical mixing, calculated for each station the values of $\partial^2 S/\partial z^2$, and determined the depth where this quantity vanishes.

This calculation of the second derivative was carried out by the rule

$$\partial^2 S/\partial z^2 = (S_{-1} + S_1 - 2S_0)/(\Delta h)^2$$

where S_0 is the value of S in the level in which the second derivative is required, and S_{-1} and S_1 are those at an equal distance Δh above and below this level, respectively.

The results of this calculation are fairly uniform, the motionless layer being found at 1000 to 1400 m. However, at some stations detection of the depth of no motion is not easy although such stations are concentrated in comparatively limited areas. The fact that the regions where the depth of no motion can be distinctly determined are clearly distinguishable from the regions where it cannot be located exactly is an indication that the dynamic conditions of water mixing are very different between the two kinds of region. It may be supposed that those areas where the exact determination of the motionless layers is not possible are characterized by the occurrence of horizontal as well as vertical mixing.

Figure 1 shows the distribution of the depth of no motion in the Atlantic, the small dots showing the positions of the stations used for drawing this diagram. The shaded areas are those where it was difficult to determine the motionless layers by our method, and it is supposed that there both horizontal and vertical mixing are taking place at nearly the same degree of intensity.

The map of the motionless layers shows that the depth of no motion is 1000 to 1100 m in the region (0° to 20°N) around the Guinea and South Equatorial Currents, extending from Cape St. Roque toward the northwestern coast of Africa. In the region south of this (0° to 20°S), we have 1100 to 1200 m, whereas in the region about 30°S we sometimes have 1200 to 1600 m. We did not try the area north of 20°N, although it appears that the motionless surface sinks deeper toward the north. To the south of 30°S, the motionless surface seems to rise gradually. But we could not locate the surfaces from this latitude on southward to 60° S, though we cannot say whether it is because these surfaces are really absent, or because they cannot be detected by our method if existing. Moreover, we have a number of patches where we cannot detect the motionless surfaces, distributed between 0° and 20°N, and near 20°S.

Apart from the question as to the authenticity of the motionless surfaces determined in the above way, it may be concluded that these surfaces as determined by our method are found in the layers from 900 to 1400 m in the regions north of 40°S.

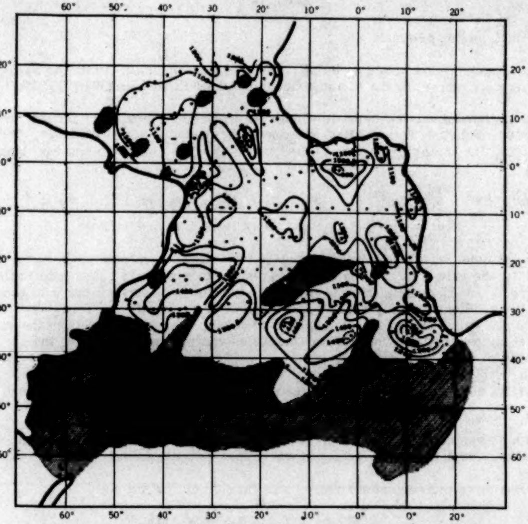

Fig. 1--Depth of the motionless layer in the Atlantic, computed from the distribution of salinity, assuming the predominance of vertical mixing; depths in meters; position of Meteor stations indicated by dots; in shaded areas the computation yields uncertain values

Acknowledgment--Numerical computations were carried out by H. Kageura and T. Yasui, senior students of the Geophysical Institute, Tokyo Imperial University.

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(Communicated manuscript received May 13, 1948;
open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

LOSS OF WAVE ENERGY DUE TO PERCOLATION IN A PERMEABLE SEA BOTTOM

J. A. Putnam

Abstract--A theory is developed for the loss in wave energy as a result of currents induced in a permeable sea bottom by wave action. This loss in energy is reflected as a reduction in the wave height as the waves move shoreward. It is shown by numerical examples that this reduction may be on the order of ten per cent on very flat beaches for wave periods and bottom materials commonly found in the ocean.

Introduction--Pressure variation at the sea bottom due to wave motion will induce currents in a permeable layer, and these currents in turn will dissipate some of the mechanical energy of the waves. At any given point on the sea bottom (see Fig. 1) there will be a flow of water into and out of the permeable bed as the pressure varies about the mean hydrostatic pressure at that point. The analysis required to estimate the energy loss due to this action is based upon the following assumptions: (1) The sea bottom at $y = 0$ is horizontal and the permeable material (sand) has uniform permeability; (2) the sand at $y = 0$ does not move; (3) the motion is two-dimensional; (4) viscous flow prevails in the sand; (5) the pressure at $y = 0$ varies sinusoidally with time and horizontal location; and (6) the fluid is incompressible. By virtue of assumption (4), Darcy's law is applicable and in conformance with the theory of ground-water motion, the problem may be analyzed as a potential flow problem.

The boundary conditions to be fulfilled are

$$y = 0; \quad \phi = \phi_0 \cos 2\pi (x/L - t/T) \qquad (1)$$

$$y = Y; \quad \partial\phi/\partial y = 0; \quad (q_y = 0) \qquad (2)$$

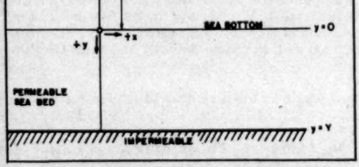

Fig. 1--Nomenclature for the analysis of percolation in a permeable sea bed

Analysis--For incompressible flow the continuity equation becomes

$$\partial q_x/\partial x + \partial q_y/\partial y = 0 \qquad (3)$$

The horizontal and vertical components of the macroscopic velocities as expressed by Darcy's law are given by

$$q_x = -\sigma \partial\phi/\partial x \qquad (4a)$$

$$q_y = -\sigma \partial\phi/\partial y \qquad (4b)$$

where

$$\phi = gZ + p/\rho \qquad (4c)$$

$$\sigma = K/\nu \qquad (5)$$

and

$$\phi_0 = gH/\cosh(2\pi h/L). \qquad (6)$$

Substitution of (4) into (3) yields the La Place equation

$$\partial^2\phi/\partial x^2 + \partial^2\phi/\partial y^2 = 0 \qquad (7)$$

for which the general solution is

$$\phi = \text{const} + (\beta e^{\alpha y} + \gamma e^{-\alpha y})(\delta \sin \alpha x + \epsilon \cos \alpha x) \quad (8)$$

Applying boundary condition (1) const = 0 and

$$\phi_o [\cos (2\pi x/L) \cos (2\pi t/T) + \sin (2\pi x/L) \sin (2\pi t/T)] = (\beta + \gamma)(\delta \sin \alpha x + \epsilon \cos \alpha x) \quad (9)$$

Comparing coefficients

$$(\beta + \gamma)\, \delta = -\, \phi_o \sin (2\pi t/T) \quad (10a)$$

$$(\beta + \gamma)\, \epsilon = \phi_o \cos (2\pi t/T) \quad (10b)$$

$$\alpha = 2\pi/L \quad (10c)$$

Substitution of (10) into (8) results in

$$\phi = (\beta e^{2\pi y/L} + \gamma e^{-2\pi y/L}) \left\{ [\phi_o \cos 2\pi (x/L - t/T)]/(\beta + \gamma) \right\} \quad (11)$$

In order to satisfy boundary conditions (2) it can be shown that

$$[\partial\phi/\partial y]_{y = Y} = (2\pi/L)(\beta e^{2\pi Y/L} - \gamma e^{-2\pi Y/L}) \left\{ [\phi_o \cos 2\pi (x/L - t/T)]/(\beta + \gamma) \right\} = 0 \quad (12)$$

from which

$$\beta = \gamma e^{-4\pi Y/L} \quad (13)$$

Accordingly, the equation for the potential function (8), which will satisfy the given boundary conditions, may be written as

$$\phi = \phi_o [e^{-2\pi y/L} + e^{-2\pi (2Y - y)/L}][\cos 2\pi (x/L - t/T)]/(1 + e^{-4\pi Y/L}) \quad (14)$$

The streamlines, corresponding to this potential distribution, may be obtained by substitution of (14) into the following form of the Cauchy-Riemann relation

$$\psi = \int (\partial\phi/\partial x)\, dy + \text{const} \quad (15)$$

The constant is arbitrary and, for convenience, has been taken equal to zero in the following discussion. Differentiation of (14) and subsequent integration of (15) yields

$$\psi = \phi_o [e^{-2\pi y/L} - e^{-2\pi (2Y - y)/L}][\sin 2\pi (x/L - t/T)]/(1 + e^{-4\pi Y/L}) \quad (16)$$

The instantaneous flow net resulting from plotting constant values of ϕ and ψ from (14) and (16) is shown in Figure 2 for a depth of porous material equal to one wave length. Flow into the sand occurs directly beneath the wave crest and flow out of the sand takes place directly beneath the trough of the wave. When the wave has progressed one-half wave length, the flow net in the sand will be identical to the one shown, but the direction of flow will be reversed. The flow net may be thought of as being propagated through the sand with the wave velocity and in phase with the wave.

The average rate of energy dissipation per unit length in the direction of motion for a unit crest width is

$$D_p = \rho/L \int_{x=0}^{x=L} \int_{y=0}^{y=Y} (q_x\, \partial\phi/\partial x + q_y\, \partial\phi/\partial y)\, dxdy \quad (17)$$

Substitution of (4) and (14) yields

$$D_p = (-\,\sigma\rho/L) \left\{ 2\pi\phi_o/[L\,(1 + e^{-4\pi Y/L})] \right\}^2 \left\{ \int_0^L \int_0^Y [e^{-4\pi y/L} + 2e^{-4\pi Y/L} + e^{-4\pi(2Y - y)/L}] \sin^2 2\pi (x/L - t/T)\, dxdy + \int_0^L \int_0^Y [e^{-4\pi y/L} + 2e^{-4\pi Y/L} + e^{-4\pi(2Y - y)/L}] \cos^2 2\pi (x/L - t/T)\, dxdy \right\} \quad (18)$$

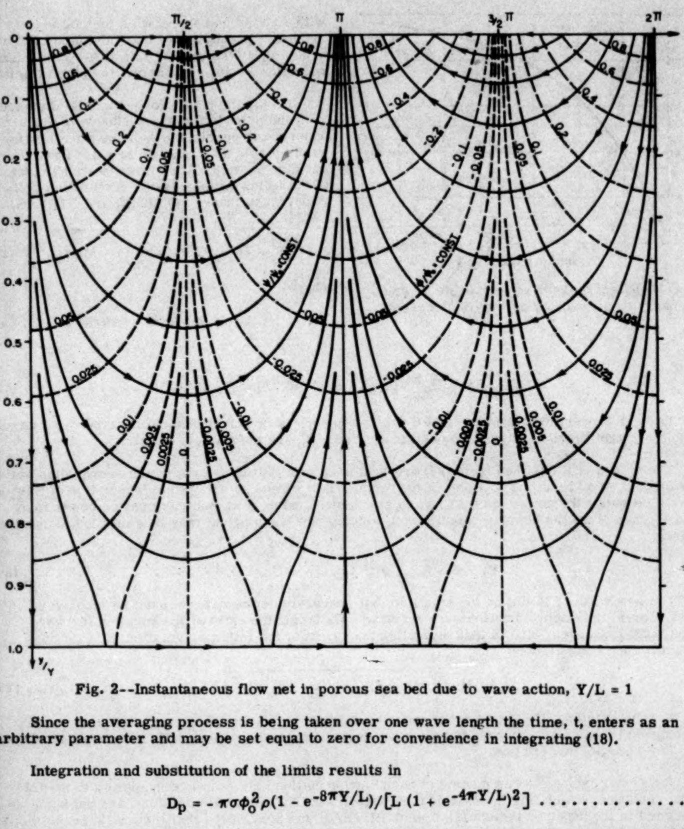

Fig. 2--Instantaneous flow net in porous sea bed due to wave action, Y/L = 1

Since the averaging process is being taken over one wave length the time, t, enters as an arbitrary parameter and may be set equal to zero for convenience in integrating (18).

Integration and substitution of the limits results in

$$D_p = -\pi\sigma\phi_0^2\rho(1 - e^{-8\pi Y/L})/[L\,(1 + e^{-4\pi Y/L})^2] \quad \ldots\ldots\ldots\ldots\ldots (19)$$

which gives the mechanical energy dissipation per unit time per unit area of sea surface due to the percolation currents induced by the wave motion. This equation, rewritten in dimensionless form, is shown in Figure 3 where it can be seen that when Y exceeds 0.3L the depth of the permeable layer no longer has any appreciable effect on the energy dissipation, and (19) may be written

$$D_p = -\pi K w^2H^2/[L\mu \cosh^2 (2\pi h/L)] \quad \ldots\ldots\ldots\ldots\ldots (20)$$

where (5) and (6) have been included. For smaller thicknesses of permeable layer the energy dissipation decreases exponentially. For a given wave period, both the wave length, L, and the wave height, H, depend upon the depth, h [WIEGEL, 1948].

To estimate the order of magnitude of the reduction in wave height due to the dissipation of mechanical energy accompanying the viscous flow of water within the sand bottom, (20) may be used

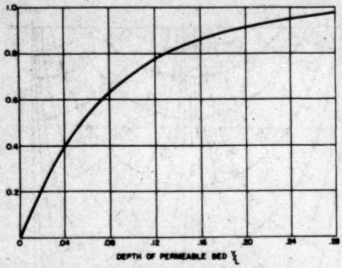

Fig. 3--Effect of depth of permeable layer on energy dissipation by percolation currents

with a numerical integration method in a manner exactly analogous to the computations presented by PUTNAM and JOHNSON [1949] for reduction in wave height due to bottom friction.

Taking the origin for horizontal distance, x, at the point in the sea surface where the water depth equals one-half the wave length, wave heights as a function of x are first computed neglecting all friction effects by means of the following expression derived in oscillatory wave theory [O'BRIEN and OTHERS, 1942].

$$H^2 = 16\, b_o P_o T/[wbL\ (1 - MH^2/L^2)]. \quad (21)$$

where

$$M = 4.935/\tanh^2(2\pi h/L) \quad \ldots\ldots \quad (22)$$

and

$$P_o = w\, b_o H_o^2 \sqrt{L_o}\ (1 - 4.935\ H_o^2/L_o^2)/7.05 \quad \ldots\ldots \quad (23)$$

In these expressions the subscript o refers to deep-water conditions. For wave crests parallel to a striaght beach no refraction occurs, and b and b_o are everywhere equal.

The values of H obtained from (21) are then used with (20) to determine the energy dissipation as a function of x, resulting in a plot of the product $D_p b$ versus x. Graphical integration of this curve then yields the power loss, ΔP, up to any desired value of x. Subtracting this power loss from P_o then gives the power available from which a new wave height may be computed, using the relation

$$P_1 = P - \Delta P = wH^2\, C_G\ (1 - MH^2/L^2)/8 \quad \ldots\ldots \quad (24)$$

The new value of H will be too small so that successive computations must be employed. Usually, only three approximations are required. By taking the ratio of the equation for wave height including energy loss to that neglecting energy loss, the following relation is found convenient for the computations

$$H_f/H = \sqrt{(P - \Delta P)/[P_o\ (1 - MH^2/L^2)]} \quad \ldots\ldots \quad (25)$$

Strictly speaking, the H occurring under the radical should be taken equal to H_f. However, this expression is small compared to the other terms and for convenience H is taken equal to the wave height neglecting friction.

Numerical example--The method of computation outlined above has been applied to the following conditions which, for the sake of comparison with bottom friction effects, are the same as those used in the paper on bottom friction by PUTNAM and JOHNSON [1949]; namely, beach slopes, 1/10 and 1/300; wave periods, 6 sec for 1/300 slope and 12 sec for each slope; waves parallel to a straight beach, b = b_o = one ft; deep-water wave height, H_o = 5 ft; permeability of bottom bed, 100 Darcys = 1.063×10^{-9} ft^2 (corresponds to a sand median diameter of 0.104 mm and 35 pct porosity); thickness of permeable bed assumed infinite (exceeds one-third wave length); viscosity of sea water, $\mu = 2.1 \times 10^{-5}$ lb sec/ft^2; and specific weight of sea water, w = 64 lb/ft^3.

The important results of the computations are presented in Tables 1 and 2 and in Figure 3. In Table 1 the effect of bottom slope on changes of wave height due to percolation loss is shown for a 12-sec period wave. Comparison of columns 6 and 11 in this table shows that by the time the waves reach the breaker point the reduction in wave height is negligible for the 1/10 slope. On the other hand, the same waves moving over the 1/300 slope experience a reduction in wave height of about seven per cent. Since the wave period was the same for both slopes, the rate of energy dissipation per foot of travel was the same in both cases. Thus the steeper slope did not provide sufficient length of travel to cause appreciable reduction in wave height. Since the steep slope had negligible effect on energy dissipation, calculations for the six-sec period waves moving over the 1/10 slope are not included.

Table 1--Effect of percolation energy loss on wave height for a 12-sec period wave on a flat and on a steep beach (H_o, 5.0 ft; sand permeability, 100 Darcys)

Distance from point where $h = L_o/2$ to breaking point	Beach slope, 1/300					Beach slope, 1/10				
	Neglecting friction		With percolation loss			Neglecting friction		With percolation loss		
	H	H/H_o	H	H/H_o	Reduction[a]	H	H/H_o	H	H/H_o	Reduction[a]
1	2	3	4	5	6	7	8	9	10	11
pct	ft		ft		pct	ft		ft		pct
0.0	5.00	1.000	5.00	1.000	0	5.00	1.000	5.00	1.000	0
20.7	4.90	0.980	4.90	0.980	0	4.90	0.980	4.90	0.980	0
41.3	4.68	0.936	4.67	0.934	0.2	4.68	0.936	4.68	0.936	0
51.7	4.63	0.926	4.60	0.920	0.6	4.63	0.926	4.63	0.926	0
62.0	4.60	0.920	4.57	0.914	0.7	4.60	0.920	4.60	0.920	0
66.1	4.58	0.916	4.54	0.908	0.9	4.58	0.916	4.58	0.916	0
70.3	4.55	0.910	4.50	0.900	1.1	4.55	0.910	4.55	0.910	0
72.4	4.55	0.910	4.49	0.898	1.3	4.55	0.910	4.55	0.910	0
74.4	4.55	0.910	4.49	0.898	1.3	4.55	0.910	4.55	0.910	0
76.4	4.58	0.916	4.51	0.902	1.5	4.58	0.916	4.55	0.916	0
78.5	4.58	0.916	4.50	0.900	1.8	4.58	0.916	4.58	0.916	0
80.5	4.60	0.920	4.51	0.902	2.0	4.60	0.920	4.60	0.920	0
82.6	4.63	0.926	4.53	0.906	2.2	4.63	0.926	4.63	0.926	0
84.7	4.68	0.936	4.57	0.914	2.4	4.68	0.936	4.68	0.936	0
86.8	4.73	0.946	4.60	0.920	2.8	4.73	0.946	4.73	0.946	0
88.8	4.83	0.966	4.72	0.944	2.3	4.83	0.966	4.83	0.966	0
90.8	4.95	0.990	4.78	0.956	3.4	4.95	0.990	4.95	0.990	0
93.0	5.10	1.020	4.90	0.980	4.3	5.10	1.020	5.10	1.020	0
95.0	5.30	1.060	5.06	1.012	4.5	5.30	1.060	5.29	1.059	0.2
97.1	5.60	1.120	5.30	1.060	5.4	5.60	1.120	5.59	1.118	0.2
99.1	6.10	1.220	5.70	1.140	6.6	6.10	1.220	6.08	1.217	0.3
100.0	6.40	1.280	5.93	1.186	7.3	6.40	1.280	6.38	1.276	0.3

[a] Comparison with frictionless wave heights.

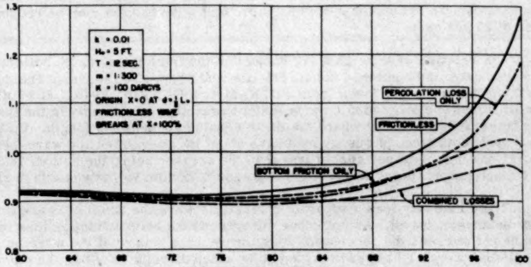

Fig. 4--Effect of energy dissipation on wave height

In Table 2 the influence of wave period on the reduction in wave height by percolation loss is shown for waves moving over the 1/300 slope. In accordance with (20) the shorter the wave period (shorter wave length) the larger will be the rate of energy dissipation per foot of travel. Thus, comparison of columns 6 and 11 of Table 2 indicates that the effect of energy dissipation becomes evident much nearer the origin of coordinates for the six-second period waves than for the 12-sec period waves. However, the difference in wave-height reduction is not large, even at the breaker point.

Table 2--Effect of percolation energy loss on wave height for a beach slope of 1/300 for short period and long period waves (H_o, 5.0 ft; sand permeability, 100 Darcys)

Distance from point where $h = L_o/2$ to breaking point	Wave period, six seconds					Wave period, 12 seconds				
	Neglecting friction		With percolation loss			Neglecting friction		With percolation loss		
	H	H/H_o	H	H/H_o	Reduction[a]	H	H/H_o	H	H/H_o	Reduction[a]
1	2	3	4	5	6	7	8	9	10	11
pct	ft		ft		pct	ft		ft		pct
0	5.00	1.000	5.00	1.000	0	5.00	1.000	5.00	1.000	0
21.7	4.90	0.980	4.88	0.976	0.4	4.89	0.978	4.89	0.978	0
43.4	4.68	0.937	4.65	0.930	0.8	4.67	0.934	4.65	0.931	0.3
54.4	4.63	0.926	4.59	0.918	0.9	4.62	0.924	4.59	0.918	0.6
65.2	4.60	0.920	4.53	0.906	1.5	4.58	0.917	4.54	0.909	0.9
69.6	4.58	0.916	4.49	0.898	2.0	4.56	0.911	4.51	0.902	0.9
73.9	4.55	0.910	4.44	0.888	2.4	4.55	0.910	4.49	0.898	1.3
76.1	4.55	0.910	4.43	0.886	2.6	4.57	0.915	4.50	0.901	1.5
78.2	4.55	0.910	4.42	0.884	2.9	4.58	0.916	4.50	0.900	1.7
80.5	4.58	0.916	4.44	0.888	3.1	4.60	0.920	4.51	0.902	2.0
82.6	4.58	0.916	4.43	0.886	3.3	4.62	0.925	4.53	0.906	2.1
84.8	4.60	0.920	4.42	0.884	3.9	4.68	0.937	4.57	0.914	2.5
87.0	4.63	0.926	4.43	0.886	4.3	4.74	0.948	4.61	0.923	2.6
89.2	4.68	0.937	4.46	0.892	4.8	4.84	0.969	4.72	0.945	2.5
91.3	4.73	0.947	4.48	0.896	5.4	4.96	0.995	4.81	0.962	3.3
93.5	4.83	0.966	4.55	0.910	6.2	5.18	1.035	4.94	0.988	4.5
95.7	4.95	0.990	4.62	0.924	7.1	5.39	1.079	5.12	1.025	5.0
97.9	5.10	1.020	4.71	0.942	7.6	5.80	1.160	5.46	1.092	5.9
100.0	5.30	1.060	4.84	0.968	8.7	6.40	1.280	5.93	1.186	7.3

[a] Comparison with frictionless wave heights.

A comparison of the effect of both bottom friction and percolation energy losses on wave-height reduction is shown in Table 3 for 12-sec period waves moving over slopes of 1/300 and 1/10. Again, the steep beach does not provide sufficient space for appreciable energy loss. However, for the flat beach, as shown in column 4, it is possible that wave heights may be reduced by amounts of the order of 25 per cent.

In Figure 4, relative wave heights are shown for the frictionless case, bottom friction only, percolation loss only, and combined bottom friction and percolation losses. The computations for the bottom friction curve were taken from PUTNAM and JOHNSON [1949]. It is of interest to note that the major effect of energy loss on wave-height reduction occurs only in the last 20 per cent of the wave travel from the point where the depth equals half the wave length. Up to about 92 per cent of the travel, both types of energy loss have about the same effect on wave-height reduction. However, over the last eight per cent of travel to the breaker point, the bottom friction effect becomes very much larger, owing to the rapid increase in bottom velocities with decreasing depth.

The combined loss requires a separate calculation since the two losses are distinctly different functions of distance of travel. Among other differences the bottom friction loss involves the cube of the wave height whereas the percolation loss involves the square of the wave height. Therefore, the two effects on wave-height reduction cannot be added directly to obtain the combined effect. The two effects are to be calculated for each position along the path of wave travel and added together locally in order to obtain the total energy loss as a function of distance.

In any event, unless the sea bottom is very permeable and very flat, the effect of percolation loss is small compared to bottom friction. If the sea bed were composed of gravel and the beach slope were very small, the percolation loss could approach the energy loss due to bottom friction, even though the friction factor for a gravel bottom might be considerably increased. However, this point has not been investigated owing to the improbability of such beaches occurring in nature.

Of the six assumptions embodied in the present theory for percolation loss, the last four are very likely realized closely in nature. The assumption of uniform permeability is perhaps the one that is least likely to be fulfilled. However, error resulting from non-uniformity is probably less than the error of assigning an absolute magnitude to the value of the permeability.

Table 3--Effect of combined bottom friction and percolation loss on wave height for a 12-sec period wave on a flat and on a steep beach (H_O, 5.0 ft, k, 0.01; sand permeability, 100 Darcys)

Distance from point where $h = L_O/2$ to breaking point	Neglecting friction both slopes H/H_O	Beach slope, 1/300 With combined losses H/H_O	Beach slope, 1/300 With combined losses Reduction[a]	Beach slope, 1/10 With combined losses H/H_O	Beach slope, 1/10 With combined losses Reduction[a]
1	2	3	4	5	6
ft					pct
0.0	1.000	1.000	0	1.000	0
20.7	0.980	0.980	0	0.980	0
41.3	0.936	0.934	0.2	0.936	0
51.7	0.926	0.920	0.6	0.926	0
62.0	0.920	0.912	0.9	0.920	0
66.1	0.916	0.904	1.3	0.916	0
70.3	0.910	0.896	1.5	0.910	0
72.4	0.910	0.894	1.8	0.910	0
74.4	0.910	0.892	2.0	0.910	0
76.4	0.916	0.896	2.2	0.916	0
78.5	0.916	0.892	2.6	0.916	0
80.5	0.920	0.894	2.8	0.920	0
82.6	0.926	0.894	3.5	0.924	0.2
84.7	0.936	0.900	3.8	0.934	0.2
86.8	0.946	0.904	4.4	0.944	0.2
88.8	0.966	0.914	5.4	0.964	0.2
90.8	0.990	0.926	6.5	0.988	0.2
93.0	1.020	0.938	8.0	1.016	0.4
95.0	1.060	0.952	10.2	1.056	0.4
97.1	1.120	0.966	13.8	1.108	1.1
99.1	1.220	0.972	20.3	1.210	0.8
100.0	1.280	0.958	25.2	1.266	1.1

[a] Comparison with frictionless wave height.

The assumption that the sand does not move at the sea bottom is valid for the major portion of the region of interest. However, in the vicinity of the breakers, sand has been observed to be in motion in many instances and is probably due to water percolation from the uprush portion of the surf. In any event, the effect is local and cannot have a large influence on the calculated results.

Acknowledgments--The work summarized in this paper was part of an extensive investigation of waves and surf made in the Department of Engineering, University of California, Berkeley, in cooperation with the Bureau of Ships, United States Navy.

APPENDIX I

Notation

b	Length of wave crest, ft
C_G	Velocity of energy advance, ft/sec
D_p	Average rate of energy dissipation (by percolation) per unit area in one wave cycle, ft lb/sec/sq ft
g	Acceleration due to gravity, ft/sec^2
h	Water depth, below still water, ft
H	Wave height, ft
K	Permeability, sq ft
L	Wave length, ft
p	Pressure, lb/sq ft
P	Power transmitted by waves in unit time
q	Macroscopic velocity, ft^3/ft^2 /sec
t	Time, sec
T	Wave period, sec

?

w	Unit weight of water, lb/ft^3
x, y	Coordinates with origin at the sea bottom
Y	Thickness of permeable bed, ft
Z	Height above potential energy datum, ft
α	A constant = $2\pi/L$
β	A constant
γ	A constant
δ	A constant
ϵ	A constant
μ	Absolute viscosity, lb/sec/ft^2
ν	Kinematic viscosity, ft^2/sec
ρ	Density, slugs/ft^3
σ	K/Σ
ϕ	Potential function
ψ	Stream function

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(Manuscript received July 19, 1948; presented at the Pacific Coast Regional Meeting, Berkeley, California, February 13, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

THE TIDE IN THE DAVID TAYLOR MODEL BASIN

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Abstract--Tidal observations were made during one week in the half-mile long David Taylor Model Basin. Harmonic constants have been derived from an analysis of this tide, which has an average range of about 0.002 inch. The discrepancy between the measured tide and the equilibrium tide is attributed to motion of the concrete basin brought about by movement of the Earth's crust. This periodic Earth movement can be separated into two parts: that due to the periodic tilting of the surface due to tidal loading near the coast, and that due to the Earth tide or deformation brought about directly by the tidal forces. The loading effect is somewhat greater than the Earth tide and is a maximum about 0.6 hr before the time of high tide on the nearby Atlantic coast. After eliminating the loading effect as nearly as possible, a value of 0.74 was obtained for the expression (1 + k - h), which is a measure of the response of the Earth to the tide-producing forces and therefore an indication of the Earth's rigidity. This is found to come within the range of results most generally accepted from the work of others.

Measurements of the very minute tide that exists in a basin were made during the period September 8-15, 1947, in the David Taylor Model Basin. Such observations are of interest not only because they bring out the small tide in the basin but also because they help to show the amount of tide in the solid Earth itself. These observations have a particular interest because the basin is so long that tidal oscillations of nearly 0.004 inch were measured near the end of the period when the moon was new and in perigee, and because the water surface is so well shielded from extraneous influences by its housing structure that a plotting of the observed readings revealed the tidal fluctuation immediately.

Tidal action in a basin--The tide-producing forces that are brought about by the attraction of the Sun and Moon upon the Earth affect both the solid Earth and the fluids upon its surface. If the Earth were a liquid that could respond freely to all the forces acting upon it, it would assume the bulging shape commonly depicted in explanation of the tides. Such a surface, which would be in equilibrium with respect to these forces, is called an equilibrium surface. It would be everywhere perpendicular to the resultant of the tide-producing forces and gravity, that is, it would be a level surface perpendicular to the plumb line.

In any relatively small basin of water on the Earth, the water surface will adjust itself parallel to the equilibrium surface if the basin is deep enough for a long wave to travel from one end to the other within the required tidal period. As the Earth revolves on its axis, the basin will pass through various portions of the bulges of the equilibrium surface. The water in the basin cannot rise and fall with the pictured rise and fall of this surface, but in remaining parallel to it, the water surface will tilt one way and another, the fulcrum or no-tide point being the center of gravity of the basin.

The amount of oscillation or tilt, and therefore the rise and fall at any point with respect to the undisturbed surface, are dependent upon known quantities and can be computed. This tide can also be measured, but the measured tide will fail to equal the computed equilibrium tide because the measurements will be made with respect to the Earth which also yields somewhat. This discrepancy can be attributed to motion of the Earth, which in turn is due to the Earth tide and also to the periodic deformation of the Earth due to the load of tidal water near the coast. These motions have tidal periods and an effort will be made to separate them.

The equilibrium tide--The tide at any point in the basin is determined by the slope of the equilibrium surface taken in the direction from the center of the basin to the point of observation and by the distance of the point from the center. The slope of the equilibrium surface is equal to the ratio of the horizontal component of the tide-producing force to gravity. If the point in question is in azimuth a from the center of the basin, then the component of the force in azimuth a will be desired. SCHUREMAN [1941] gives the ratio of this force to gravity as

$$F_a/g = 9(U \sin 2Y \cos a \; \Sigma fC_0 \cos E_0)/8$$
$$+ \; 3(UP_1 \; \Sigma fC_1 \cos \; E_1 - X_1 \;)/2$$
$$+ \; 3(UP_2 \; \Sigma fC_2 \cos \; E_2 - X_2 \;)/2 \quad \ldots\ldots\ldots\ldots (1)$$

where F_a is the horizontal component of the tide-producing force in azimuth a; g is acceleration of gravity; U is ratio of mass of Moon to mass of Earth multiplied by the cube of the sine of lunar parallax (for solar constituents, mass of Sun and solar parallax are to be used); Y is latitude of the basin, which is 38° 58′ 30″ N; C_0, C_1, and C_2 are mean coefficients of the various long period, diurnal, and semi-diurnal constituents. (In this computation, the long period components were found to be negligible). The following were used: K_1, O_1, P_1, Q_1, M_2, S_2, N_2, and K_2; f is the node factor which makes the coefficients applicable to the year in question. E_0, E_1, and E_2 are the arguments for the various constituents;

$$P_1 = (\cos^2 2Y \cos^2 a + \sin^2 Y \sin^2 a)^{1/2} \quad \ldots\ldots\ldots\ldots (2)$$

$$P_2 = \cos Y \,(\sin^2 Y \cos^2 a + \sin^2 a)^{1/2} \quad \ldots\ldots\ldots\ldots (3)$$

$$X_1 = \tan^{-1}\left[(\sin Y \sin a)/(-\cos 2Y \cos a)\right] \quad \ldots\ldots\ldots\ldots (4)$$

$$X_2 = \tan^{-1}\left[\sin a/(\sin Y \cos a)\right] \quad \ldots\ldots\ldots\ldots (5)$$

$$a = 106° \; (S106°W)$$

Now if HI is the height of the tide at the point of observation and D is the distance of that point from the center of the basin, then the slope is

$$HI/D = F_a/g \text{ or } HI = DF_a/g \quad \ldots\ldots\ldots\ldots (6)$$

Hence if the distance D, which in these observations is 1334 ft, is included in the coefficient of each constituent in (1), the solution of that equation will give the height of the tide. The amplitudes of the diurnal and semi-diurnal constituents, as represented by $3UP_1C_1D/2$, and $3UP_2C_2D/2$, and the epochs, as represented by X_1 and X_2, are given in Table 1. The height of the tide was computed for each hour of the period of observation and the result is discussed later.

Table 1--Harmonic constants

Item	Equilibrium tide		Observed water tide		Amplitude ratio	Phase difference
	H (C)	kappa (c)	H (B)	kappa (b)	B/C	b - c
	in	°	in	°		°
M_2	0.000922	100.2	0.000720	73.5	0.781	-26.7
S_2	0.000429	100.2	0.000300	78.1	0.700	-22.1
N_2	0.000178	100.2	0.000149	73.8	0.837	-26.4
K_2	0.000117	100.2	0.000082	78.1	0.701	-22.1
K_1	0.000430	84.6	0.000318	105.6	0.739	21.0
O_1	0.000306	84.6	0.000228	76.0	0.747	- 8.6
P_1	0.000142	84.6	0.000105	105.6	0.739	21.0
Q_1	0.000059	84.6	0.000039	65.1	0.654	-19.5
				Weighted mean[a]	0.752	

[a] Mean of amplitude ratios weighted according to size of amplitude of equilibrium constituent.

The basin and apparatus--The David Taylor Model Basin is at Carderock, Maryland, near the Potomac River, and suburban to Washington, D. C., in approximate latitude 38°58′30″ N, longitude 70°11′30′′W. There are two long narrow concrete basins lying side by side housed in a long concrete structure with a concrete arched roof. At intervals along the wall there are vents through which blowers can bring in outside air and other vents for the escape of inside air. In order to clear the very humid air, these vents were opened and the blowers turned on each day from about midnight to 07^h30^m. At other times the vents were kept closed.

The basin in which the observations were made is about 2773 ft long, 52 ft wide, and 22 ft. deep, and lies in a W16°N to E16°S direction. One gage was located 57 ft from the west end and the other

48 ft from the east end. Making observations in both ends of the basin permitted the determination and elimination of changes in level due to evaporation and seepage and helped reduce the effect of observational errors. The west end of the basin is considered the point for which the tide is to be determined, and all computations have been made for that end.

The observations were taken during a period when model testing was suspended so that engineers could test the alignment of new rails. A wooden bulkhead 1890 ft from the east end separated the basin into two parts, but for the purpose of improving the chances of success of these observations, a section about 15 ft wide and 1 1/2 ft deep was removed in order to increase the length of the oscillating surface and thus magnify the vertical motion to a size more easily measured.

The gages and other apparatus used for making the observations were furnished and installed by the David Taylor Model Basin. The gages were plunger and dial type indicating gages. The smallest division was 0.0001 inch, one revolution of the pointer was 0.02 inch, and 20 revolutions could be accommodated. Each gage was mounted on a substantial wooden arm attached to a rigidly constructed wooden bridge that was supported by two floating punts. The arm extended over the side of the basin so that the plunger of the gage rested upon a flat section of steel rail on the concrete wall of the basin. Thus the gage would rise and fall with the rise and fall of the water. The setting for the initial readings of the gages was entirely arbitrary, there being no attempt made to correlate the two. The gages were 2668 ft apart.

The observations--Each gage was read every half hour so that an observation was made every 15 min. Though there was no visible motion of the water during the period of observation, there was usually some oscillation indicated by the gages. During each observation the motion of the dial pointer was carefully watched, and the four maximum and four minimum points reached during four swings of the pointer were recorded. This usually took about five minutes. In some instances, however, the water was so quiet that there was practically no motion of the pointer during a five-minute period. The time of the beginning and end of each observation was also recorded. For each set of readings, the heights were averaged as were also the times. The results for each gage were plotted and are shown in Figure 1. Note that high tide at one end is simultaneous with low tide at the other. The time here and throughout this paper is 60th meridian time.

The general downward drift of the water level at both gages which is due probably to evaporation or seepage or both. It is desirable to eliminate as far as possible all non-tidal variations from the observations. The variation in mean level was obtained by taking an average of the first 50 consecutive half-hourly observations (an approximate tidal day) and plotting the mean at the midpoint of the group, then by moving along hour by hour repeating the process. This provided a well-determined mean level for all but the first and last 12 hours, for which it was estimated. The result is shown by the solid line in Figure 1.

Note that the downward drift in level is more rapid at one end of the basin than at the other. While this variation is in phase with the very small long-period variation of the tide (fortnightly and monthly), most of it is doubtless due to non-tidal causes, such as possible absorption of water by the punts.

The general downward trend of the water level was eliminated by scaling the hourly heights of the observed level referred to the sloping mean level as a datum and replotting them to a horizontal datum. Figure 2 shows the curves for both ends of the basin plotted to the same datum. The process to this point has eliminated any long-period tide or other long-period variation but not variations with a period of a day or less. The tidal variation is easily discernible; the tilting of the water surface due to the tidal forces results in a rise at one end accompanied by an equal fall at the other. There is also shown, however, a diurnal variation in the general level as evidenced by the simultaneous rise and fall of the level at both ends of the basin which can not be tidal. Though a corresponding variation was not noticeable on the air temperature and humidity records, the diurnal variation in level is probably due, at least in part, to a variation in evaporation brought about by the periodic saturation of the air during the day and its dehumidification when the blowers were turned on. It should properly be considered a diurnal variation in the downward drift of mean level.

This variation together with many observational irregularities can be eliminated by inverting the curve for the east end and then averaging it with the one for the west end. The observed tide thus adjusted is shown in Figure 3 and represents the tide at the west end of the basin as nearly as it can be obtained from these observations. The equilibrium tide as computed from (6) is also shown in this figure.

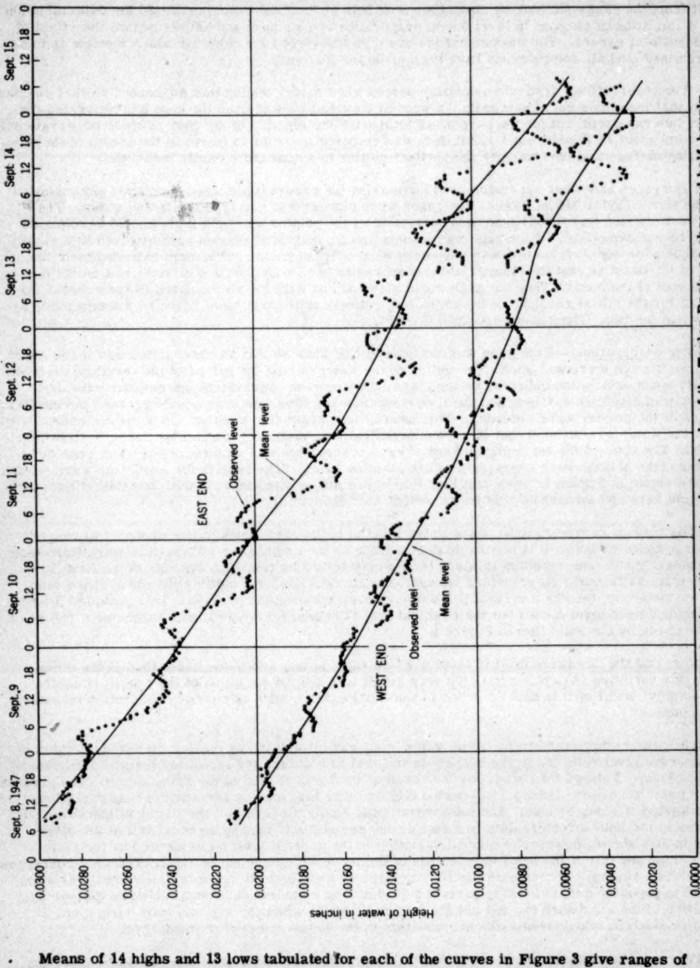


Fig. 1--The water levels at the east and west ends of the Taylor Basin as observed half-hourly clearly show tidal fluctuation

Means of 14 highs and 13 lows tabulated for each of the curves in Figure 3 give ranges of 0.00181 inch and 0.00241 inch for the observed and computed tides respectively. (Each 0.001 inch of rise represents a surface tilt of 0.013 sec of arc.) The ratio of observed to computed range is 0.751. The observed highs and lows occurred on the average 1.05 hr earlier than the computed.

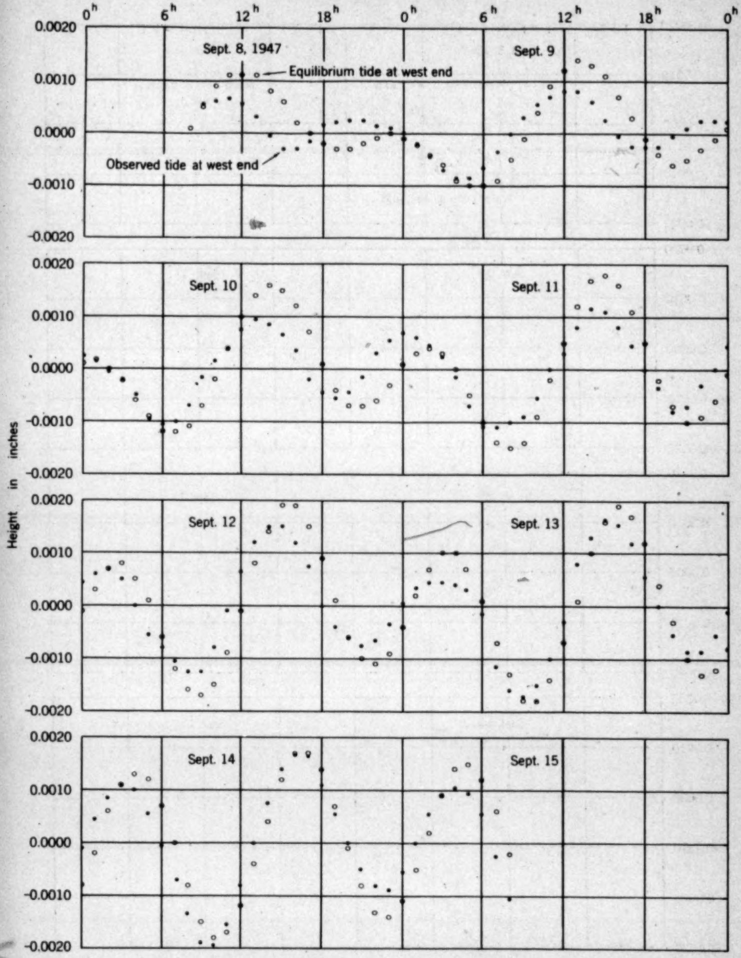


Fig. 2--Hourly levels scaled from the mean level lines of Figure 1 as datum; non-tidal diurnal variation shown by the broken line

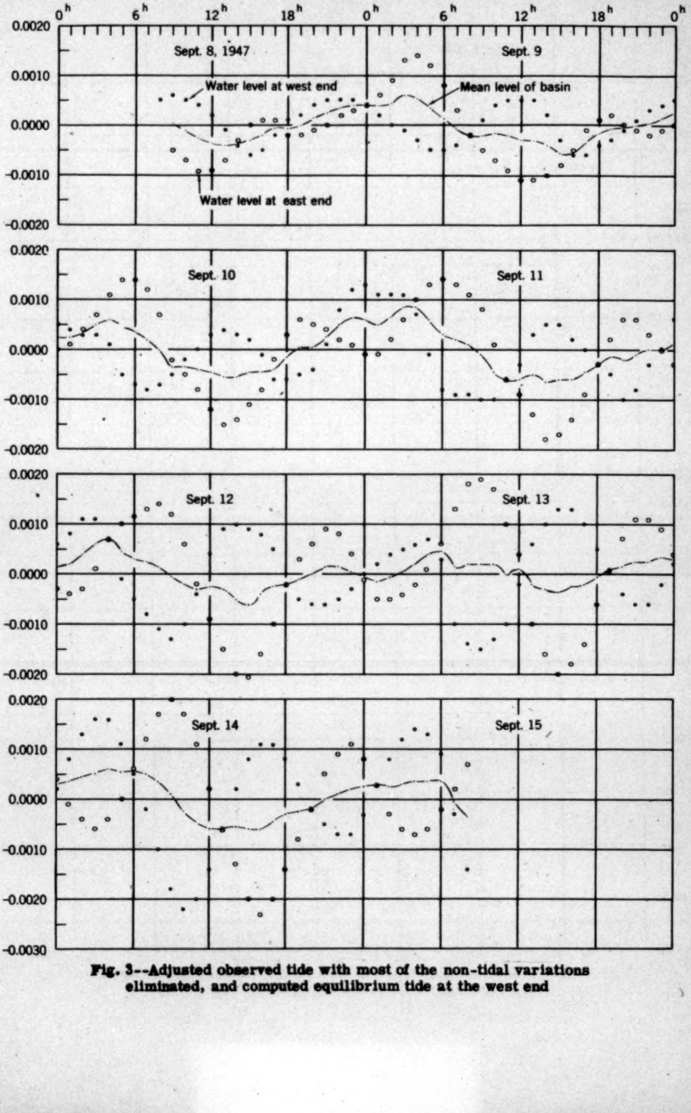


Fig. 3--Adjusted observed tide with most of the non-tidal variations eliminated, and computed equilibrium tide at the west end

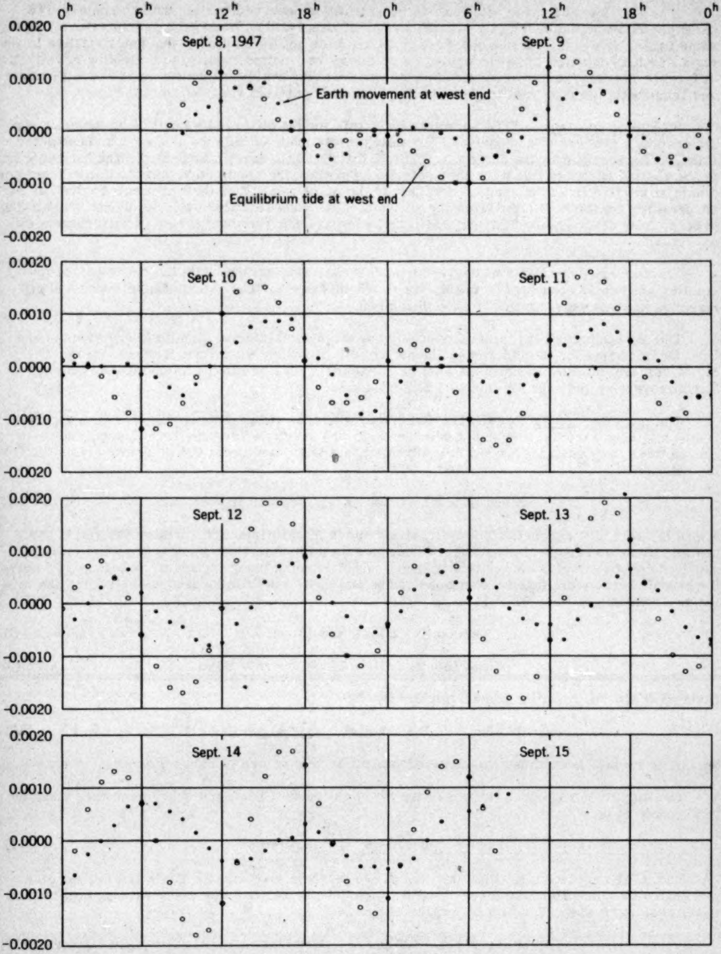


Fig. 4--The difference between the two curves in Figure 3 is due to movement of the Earth which is shown here in relation to the equilibrium tide; the Earth movement is composed of Earth tide and effect of tidal loading near the coast

It is startling at first to note that the observed tide occurred earlier than computed. The same phenomenon was noted in a two-day series of observations obtained a year previously in the same basin. However, the tide observed in the basin is not the motion of the water relative to the rigid Earth as depicted by the computed curve but rather motion relative to a yielding Earth. The difference between these two curves, as obtained from the hourly ordinates, is shown in Figure 4 and represents the motion of the Earth. The computed curve is repeated in this Figure.

Harmonic constants--Tidal harmonic constants for the observed water tide in the basin were obtained by a process of comparison. An analysis was made of both the observed and computed tides, as represented by the curves in Figure 3 for the same seven-day period. The harmonic constants for the observed tide were then obtained by making the assumption that the uncorrected constants as derived from the analysis would bear the same relation to their corrected values as the uncorrected constants derived from the analysis of the computed tide would to theirs. This is the process fully described by SCHUREMAN [1941] for analysing a short series of tidal current observations.

The corrected constants as derived from the analysis, together with the constants for the equilibrium tide as computed from (6), are shown in Table 1. The ratios of amplitudes and differences in phase lags, or epochs, are also given.

The M_2 constants represent very nearly the mean semi-diurnal amplitude and epoch of the tide, the constants for the other constituents merely producing variations from the mean. The M_2 values are, moreover, much the best determined. Therefore in the following discussion of Earth movement, only the M_2 tide will be considered.

The movement of the Earth--The Earth movement, as represented by the curve in Figure 4, can be analysed harmonically, but since constants are available for both the computed and observed tides, the constants for any constituent of the Earth movement can be derived from the folling relation

$$M \cos (E - m) = C \cos (E - c) - B \cos (E - b) \qquad (7)$$

where M and m are respectively amplitude and epoch of constituent of Earth movement; C and c are amplitude and epoch of constituent of computed equilibrium tide; B and b are amplitude and epoch of constituent of observed tide in basin; and E is constituent argument, as before. To solve for M and m, two simultaneous equations can be set up by substituting successively for E the numerical values b and b + 90°. Thus

$$M \cos (b - m) = C \cos (b - c) - B \qquad (8)$$

$$M \cos (b - m + 90) = C \cos (b - m + 90) \qquad (9)$$

Dividing (8) by (9), reducing and solving for m,

$$m = b - \cot^{-1} \left\{ [B - C \cos (b - c)] / C \sin (b - c) \right\} \qquad (10)$$

leaving M readily determined by substitution of numerical values of m in (8) or (9).

The amplitude and epoch (kappa) of the M_2 constituent of the Earth movement were found by this method to be

$$M = 0.000427 \text{ inch} \qquad m = 149.4^\circ \qquad (11)$$

The movement of the Earth is the sum of two periodic motions: the Earth tide, or the direct yielding to the tide-producing forces, and the tilting of the surface due to the varying load of tidal water near the coast. This may be expressed as

$$M \cos (E - m) = T \cos (E - t) + L \cos (E - \ell) \qquad (12)$$

where T and t are amplitude and epoch of Earth tide, and L and ℓ are amplitude and epoch of loading effect. Both component motions are tidal and therefore have the same mean period though not necessarily the same phase or amplitude. It is desired to separate as nearly as possible the Earth tide from the loading effect and to determine the phase and amplitude of each.

While the whole difference between the apparent Earth movement and the Earth tide is here considered to be a tilting of the Earth due to the varying load of tidal water near the coast, it is recognized that the varying mass of this tidal water exerts an attractive force to which the water in the basin can respond. When it is high water near the coast, the additional weight of water there will cause the Earth to tilt downward at the east end and upward at the west end of the basin. At this time the attraction of the additional mass of water will cause the water surface of the basin to tilt upward at the east end and downward at the west end. The effect on the observations is the same as though the loading effect were somewhat greater than it really is. The two phenomena have the same period and are in phase, and in this discussion the combined effect is treated as tilting of the Earth due to loading.

Likewise, the alternate bulging and flattening of the Earth, which is brought about by the tidal forces, will have an effect upon the plumb line and therefore upon the tilt of the surface of the water in the basin. The height of the water with respect to a rigid Earth then will not be merely C, the equilibrium amplitude, but can be expressed as $(1 + k)C$. This added effect has the same period as the Earth tide and is in phase with it so that the two cannot be separated. Since the height of the water in the basin is measured with respect to an Earth that yields somewhat to the tide-producing forces, if the height of the true Earth tide is hC, then, omitting the loading effect, the measured tide in the basin would be $(1 + k - h)C$. The expression $1 + k - h$ is a measure of the response of the Earth to the tide-producing forces and therefore an indication of the Earth's rigidity. (For a complete discussion see LAMBERT [1931].) It is a quantity usually sought by those who have worked with Earth tides. It may be thought of as $1 - (h - k)$, and in this discussion the combined effect, $(h - k)C$, is considered to be Earth tide and labelled T. Therefore

$$1 + k - h = 1 - T/C \quad \ldots\ldots\ldots\ldots \quad (13)$$

which will be sought. Note that, if there were no effect of tidal loading, the expression $1 - T/C$ would be the ratio of the measured tide in the basin $(C - T)$ to the equilibrium tide (C).

The amplitudes and epochs of the Earth tide and loading effect in (12) are unknowns. Since this equation can be expanded into two simultaneous equations, if two of the quantities can be confined within restricted limits, then values can be substituted within these limits and the equation can be solved for the other two unknowns. Consider the cases of t and ℓ.

For physical reasons, the lag of the Earth tide behind the equilibrium tide must be very small. If it is assumed to be zero, then the epoch of the Earth tide will be equal to that of the equilibrium tide and (only the M_2 constituent being considered)

$$t = c = 100.2^\circ \quad \ldots\ldots\ldots\ldots \quad (14)$$

leaving three unknowns to be solved for. Equation (12) can be solved for T and L in terms of ℓ by obtaining simultaneous equations through the successive substitution of t and $t + 90^\circ$ for E, obtaining

$$T = M \cos (t - m) - M \sin (t - m) \cot (t - \ell) \quad \ldots\ldots\ldots\ldots \quad (15)$$

and

$$L = M \sin (t - m) / \sin (t - \ell) \quad \ldots\ldots\ldots\ldots \quad (16)$$

After substituting the values indicated in (11) and (14)

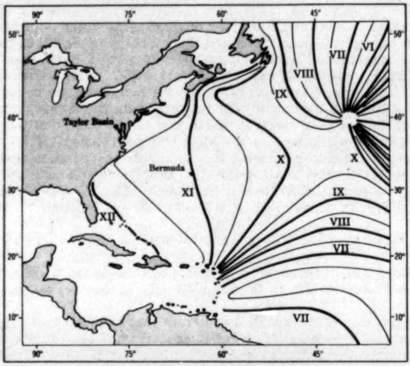
$$T = 0.000279 + 0.000323 \tan (\ell - 10.2^\circ) \quad \ldots\ldots\ldots\ldots \quad (17)$$

$$L = 0.000323 / \sin (\ell - 100.2^\circ) \quad \ldots\ldots\ldots\ldots \quad (18)$$

It is seen from (15) that if $\ell = m = 149.4^\circ$ the amplitude of the Earth tide is zero. Smaller values of ℓ will make T negative and therefore need not be considered. With ℓ, as with t, it can be assumed that the lag between cause and effect will be so small that it can be considered zero. An upper limit for ℓ will be determined by the latest time maximum loading can occur.

The loading effect has been spoken of as due to the varying load of tidal water near the coast. The possibility of the tide in the Potomac River or in Chesapeake Bay being primarily responsible for the loading effect was considered and rejected. There is always a complete tide wave in the bay progressing from south to north, so that within that comparatively small area there is always a low to counterbalance the effect of a high, and any small loading effect that remained would be of no consequence. Somewhat the same condition exists in the Potomac River where, moreover, the change in volume is much smaller.

If the tide in the Atlantic is accepted as responsible for the loading tilt, then the latest possible time of maximum loading would be when it is high tide at the coast. Tide observations on the outer coast from Atlantic City to Daytona Beach show that the tide is nearly simultaneous along this stretch, the M_2 Greenwich epochs varying by only 15° from 355° to 370° [U. S. COAST AND GEODETIC SURVEY, 1942]. Even in the ocean at Bermuda this epoch is also about 355°. These epochs can be referred to the meridian of the Taylor Basin by subtracting twice the longitude of the basin (154°), giving epochs of 201° to 216°. MARKOWITZ and BESTUL [1941], using the tide tables, computed a rounded interval of seven hours which is equivalent to a value of 203° for ℓ. These values are all in a region which roughly defines the upper limit of ℓ.



Fig, 5--Harris' cotidal lines for the western North Atlantic help in estimating the time of maximum loading effect

It is probable that maximum loading would occur some time before the high water crest reached the coast. Not a great deal is known about the course of the tide in the open ocean, but several authorities have depicted its probable course by means of cotidal maps on which the progress of high tide is shown in lunar hours after the Moon's transit of Greenwich. Harris' cotidal lines for the nearby Atlantic Ocean [HARRIS, 1904], which are reproduced here as Figure 5, were drawn without benefit of recent observations at Bermuda which indicate that the XI-hour and the XI 1/2-hour lines should bend eastward so as to lie east of that island. Leaving the other lines about as they are and considering only the area extending from the coast out to about X-hour line, it is believed probable that the greatest load of water in this area occurs when it is high water along the XI 1/2-hour or XI 1/2-hour line. This estimate considers both the shape of the area and the fact that the water rises only a small amount during the hour or half hour before high water. These times correspond to Greenwich epochs of 330° and 345° for which ℓ becomes 176° and 191°, respectively. A mean value for ℓ would be 183° with corresponding values of 0.000326 inch for L, 0.000238 inch for T, and 0.742 for the quantity 1 - T/C.

Table 2 contains values obtained by solving (17) and (18) using various values for ℓ that are within what has been considered the range of possibility. It is based upon the assumption that there is no lag between the equilibrium tide and the Earth tide. Before considering this table further, it might be well to investigate the effect of possible lags on the conclusions that may be obtained. For this purpose, Table 3 was constructed by solving (15) and (16) for ℓ and L using values of t ranging from 95° to 110° and values of T obtained through the ratios mentioned in the next paragraph. Omitting fractions, these values of t correspond to lags of -5°, 0°, +5°, and +10°. It will be noted that for a particular ratio, ℓ changes very slowly with changes in t. The variation is so small, compared to the attainable accuracy, that it can be concluded that any value of ℓ obtained for the condition of no lag, as in Table 2, will be valid for any lag that is possible in nature.

Something is known of the value of T through the ratio 1 - T/C as obtained from the work of others. To mention three whose observations covered a year or more, SCHWEYDAR [1921] obtained a ratio of 0.841, CORKAN [1939] obtained 0.77, and MICHELSON and GALE [1919] obtained 0.690. These values have been included in Table 2 by first solving (17) for ℓ, obtaining

Table 2--Values for M_2 constituent of loading effect and Earth tide

t	ℓ	T	(1 - T/C)	L
°	°	in/1000		in/1000
100.2	149.4	0.000	1.000	0.427
100.2	168	0.147	0.841	0.349
100.2	176	0.197	0.786	0.333
100.2	178.5	0.212	0.770	0.330
100.2	183	0.238	0.742	0.326
100.2	191.4	0.286	0.690	0.323
100.2	201	0.341	0.630	0.329
100.2	216	0.435	0.526	0.359

Table 3--Effect on ℓ and L of possible changes in t and T

t	ℓ	T	(1 - T/C)	L
°	°	in/1000		in/1000
95	168.6	0.147	0.841	0.362
100	168.0	0.147	0.841	0.350
105	167.1	0.147	0.841	0.338
110	166.0	0.147	0.841	0.327
95	178.9	0.212	0.770	0.349
100	178.5	0.212	0.770	0.331
105	177.7	0.212	0.770	0.313
110	176.5	0.212	0.770	0.295
95	191.1	0.286	0.690	0.349
100	191.4	0.286	0.690	0.324
105	191.4	0.286	0.690	0.300
100	190.8	0.286	0.690	0.275

$$\ell = 10.2^\circ + \tan^{-1}\left[(T - 0.000279)/0.000323\right] \quad . \quad (19)$$

If it is assumed that the true value of 1 - T/C lies within this range of values, it will provide a criterion for checking the validity of the values obtained from these observations.

It will be seen that the range covers values of ℓ from 168° to 191°, which corresponds to cotidal hours X 3/4 to XI 1/2 and includes what was considered the probable times of greatest loading. For the greatest loading to occur at the time of high water at the coast ($\ell = 201^\circ$ to 216°), the ratio 1 - T/C would be considerably beyond the range of values obtained by these observers which would imply a less rigid Earth than is usually accepted. For the most probable value of ℓ from the Carderock observations (183°), the ratio 0.742 is just above the mid-point of the range of values. It will be noted that for this value of ℓ, the loading effect is greater than the Earth tide.

Summary of results--Following are the principal points brought out by, or readily deduced from, the foregoing discussion.

(1) The observed range of tide of one end of the Taylor Basin varied from 0.0004 inch at the beginning of the period of observation to 0.0038 inch near the end of the period when astronomical conditions favored large tides. The mean range may be taken roughly as $2M_2$ which is 0.0014 inch. The ratio of observed to equilibrium ranges 0.75.

(2) The discrepancy between the observed and equilibrium tides is due to movement of the Earth, for which $2M_2$ equals 0.0009 inch.

(3) The total Earth movement is composed of Earth tide and tilting due to the varying load of tidal water near the coast. The two effects cannot be separated rigorously but probable values can be obtained. At this location, they probably differ in phase by about 80°, and the loading effect is greater than the Earth tide. The value of $2M_2$ for one end of the basin is about 0.0005 inch for the Earth tide and over 0.0006 inch for the loading effect. Angular values for M_2 (semi-range) representing the tilting of the Earth's surface above or below its mean position are 0.003 sec for the Earth tide and 0.004 sec for the loading effect.

(4) The greatest loading effect occurs about 0.6 hr before the time of high water on the nearby coast.

(5) The most probable value for 1 + k - h, which is 1 - T/C, is 0.74.

(6) The amplitude T has been attributed to the Earth tide, but as mentioned earlier

$$T = (h - k)C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

where hC is the true Earth tide. LAMBERT [1931] suggests that k is about h/2, so that

$$2\,T/C = h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (21)$$

Since the ratio obtained for T/C from these observations is 0.26, then h = 0.5 and the vertical motion of the whole basin due to the Earth tide alone has an average semidurnal range of about six inches.

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(Manuscript received August 20, 1948; presented by title at the Twenty-Ninth Annual Meeting, Washington, D. C., April 21, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

FLOW OF PONDED WATER INTO DRAIN TUBES IN SOIL OVERLYING AN IMPERVIOUS LAYER

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(Journal Paper No. J-1472, Soils Subsection, Iowa Agricultural Experiment Station, Ames, Iowa, Project 998)

Abstract--On the assumption that uniform, water-saturated soil covered by ponded water, and overlying an impervious layer is drained by equally spaced circular drain tubes at equal depth, two sets of expressions for the velocity potential, stream potential, the drain flux, and the surface inflow distribution are derived. Each alternate expression yields the same result, one set of results being useful in numerical work when the impervious layer is at shallow depth, the other when the impervious layer is at great depth. Parameters are soil permeability, drain depth, drain spacing, drain radius, depth to the impervious layer, and depth of ponded water. The method of complex variable is used. The results are of practical interest in the problem of artificial drainage of land and in the problem of leaching.

Introduction--In 1940 two formulas [KIRKHAM, 1940 a and b] were presented which gave the theoretical rate of flow of water into drains for water-saturated, uniform soil overlying an impervious layer. The derivations of these formulas were not then given, nor have they since appeared in the literature. It is the purpose of this paper to present derivations of these formulas (including certain terms there neglected and introducing also an additional parameter, the thickness of ponded water), and at the same time to obtain velocity and stream potentials and other quantities associated with the flow; and to discuss the results in application to the practical problem of artificial drainage of land by underdrains, to the problem of leaching of nutrients from the soil into drains, and to the problem of leaching of harmful salts into underdrains by flooding the affected areas.

In deriving the formulas, two sets of equations, differing in appearance but yielding the same results will be obtained; one suitable for convenient calculation when the drain spacing is large compared to a certain depth to the impervious layer, and the other when the drain spacing is small, either solution being suitable for intermediate spacings. The formulas, obtained in the form of infinite series, are rapidly convergent, if the proper series is chosen. For slide rule accuracy (three significant figures), no more than the zero order, and first order terms are needed; and in many cases the zero order term is sufficient.

Although the formulas are obtained for a large number of equally spaced drains, since the results are of general validity, the case of a single drain is also included, this case corresponding analytically to a number of drains at infinite spacing. The results may also be used when the soil is not saturated to the surface, provided the water table is approximately horizontal. The results may also be used to calculate the permeability of the soil.

The analytical methods used in this paper will follow those of KIRKHAM [1945 a] the results being obtained in terms of logarithmic, trigonometric, and hyperbolic functions which are well known and extensively tabulated. For a limited treatment of this problem in terms of the Jacobi elliptic functions (but expressions for the drain flux are not there given explicitly in terms of the original parameters, drain depth, drain radius, and other factors), reference is made to a paper by GUSTAFFSON [1946]. HOOGHOUDT [1940] has also considered certain aspects of the problem. He gives some rather extensive tabulations of results.

Notation--The mathematical notation is that due to Stokes and described in the introduction to his collected Mathematical and Physical Papers. Thus, a/bc means the same as a/(bc); a/b + c the same as (a/b) + c. Also tan a/2 = tan (a/2).

$$\tan^{-1} \tanh ab/c \cdot \cot ab/c = \tan^{-1} \left\{ [\tanh (ab/c)] [\cot (ab/c)] \right\}$$

$$\log_e (a + b)/c + a = \left\{ \log_e [(a + b)/c] \right\} + a$$

Analysis

Figure 1 shows the geometry for the present problem. Homogeneous soil, of permeability K, covered with water of thickness t, overlies an impervious layer at depth h. A large number of circular drains of radius r are embedded in the soil at equal spacing a and depth d. The drains and soil are assumed to extend a great distance horizontally, making the problem one in two dimensions. The origin for coordinates is chosen at the center of a drain, the y axis being vertical upward and the x axis horizontal to the right, the vector distance from the origin to any point being given by $z = x + iy$, where $i = (-1)^{1/2}$. The walls of the drains are assumed at constant potential; that is, the drains are taken as running full with negligible back pressure. (This theory, except as an approximation, does not apply generally to the problem of flow into tile drains, since flow occurs only in the small spaces between the individual tiles with a resultant variation in potential along the tiles. If the tile drains are covered with a highly pervious material, as gravel, this theory will apply.) If the soil is not saturated to the surface but there is an approximately horizontal water table [CHILDS, 1947], t in Figure 1 is taken equal to zero and d is measured to the level of the ground water instead of to the surface of the soil. Readers not desiring to follow mathematical details may skip the "Analysis" and go to "Results and discussion."

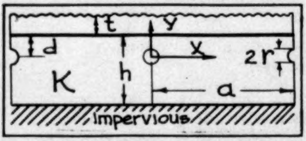

Fig. 1--Section of field with ponded water and drain tubes; soil permeability, assumed uniform, is K, depth of drains d, spacing a, diameter 2r; thickness of ponded water is t, depth from soil surface to impervious layer h; Eq. (11) or (15) gives Q, the quantity of water entering unit length of drain tube per unit time for the parameters shown in this figure

Laplace's equation for groundwater flow is assumed valid. That is

$$\nabla^2 \Phi = 0$$

where

$$\Phi = (k\gamma g/\mu)(p/\gamma g + y) = (k\gamma g/\mu)\phi = K\phi$$

Here k is the soil permeability as used by MUSKAT [1937] and others, μ the viscosity of the soil water, γ the density of the soil water, g the acceleration of gravity, p the pressure at a point in the soil, y the vertical coordinate of the point where the pressure is p, K is equal to $k\gamma g/\mu$, and

$$\phi = (p/\gamma g + y) \qquad (1)$$

The lumped constant K, often used as the permeability constant [RICHARDS, 1940, MUSKAT, 1937, p. 72], represents physically the infiltration rate, say in inches per day for a water-saturated vertical column of soil whose upper and lower surfaces are at atmospheric or some other fixed pressure, and whose upper surface is kept covered with a thin layer of water. The potential ϕ in engineering language is more commonly known as the hydraulic head. Physically, ϕ is the height above (or below) some arbitrary level (here, a horizontal plane through the drain axes) at which soil water would stand in a test pipe inserted in the soil. In such a test pipe $p/\gamma g$ is the distance of the water level above the pipe bottom and y (y may be positive or negative) the distance of the pipe bottom to the reference level. It may be remarked that the water level in such a test pipe will correspond to the level of the water table only if the ground water is in static equilibrium. The most pertinent characteristic of the potential ϕ is that the expression $K\partial\phi/\partial s$ gives the quantity of water per unit area per second passing through an area perpendicular to the direction s. For example, at a distance r_1 from the axis of a drain tube about which there is uniform radial flow, the flow rate per unit area normal to r_1 is $K\partial\phi/\partial r_1$. If the drain is of radius r, the total quantity of water entering unit length of drain is $2\pi r K \, \partial\phi/\partial r_1$, where the derivative is evaluated at $r_1 = r$.

Evaluation of the potentials--With ϕ defined as in (1), the differential equation to be satisfied is $\nabla^2\phi = 0$ subject to the following Boundary Conditions $y = d$

$$\phi = (p_A/\gamma g + t + d) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Condition (I)}$$

where p_A denotes atmospheric pressure.

At the surface of a drain, say the upper surface, $y = r$, $x = 0$

$$\phi = (p_A/\gamma g + r) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Condition (II)}$$

At the impervious layer $y = -h + d$

$$\partial\phi/\partial y = 0 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Condition (III)}$$

The appropriate image system is shown in Figure 2. The images are located at the same relative positions with respect to the soil surface and the impervious layer as in the case previously considered [KIRKHAM, 1945a]; they differ only, but importantly, in the matter of sign. Consideration of the image array as first a series of columns and then a series of rows leads to the two desired sets of potential functions and expressions for computation of the drainage flow. The drains considered in columns are numbered $m = 0, 1, -1, 2, -2, \ldots, \infty, -\infty$; while in rows the drains are grouped in pairs at $n = 0, 1, -1, \ldots, \infty, -\infty$. Sinks are indicated plus (+); sources are indicated minus (-). The location of the y-coordinate of each row of drains is shown. These values, $y = 0, 2d, 2h, 2h + 2d, -2h + 2d, -2h, \ldots$, are needed for writing down the potential functions.

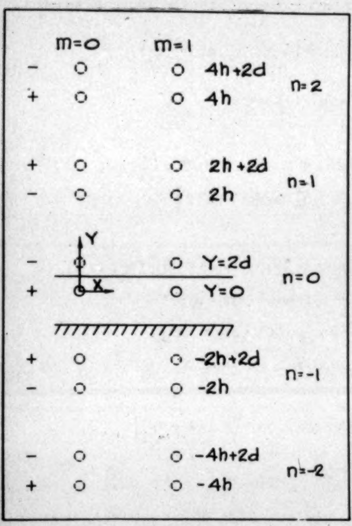

Fig. 2--Image array corresponding to Figure 1; the actual drain tubes are located at $y = 0$; the images extend vertically and horizontally to infinity, only a few such as at $y = 2d$ and $2h$ are shown; drain tubes and images which receive water (sinks) are indicated with a plus sign; those emitting water (sources) with a minus sign; consideration of the array first as a series of columns at $m = 0, 1, -1$, etc., and then as a series of double rows at $n = 0, 1, -1$, etc., leads to alternate solutions of the problem for wide and narrow spacing of drains

As in a previous paper [KIRKHAM, 1945a], $2q \log_e z_1$ is taken as the fundamental (complex) potential form. Here $2q$ is a flux coefficient, q is positive for sinks and negative for sources; and z_1 is the vector distance from a drain in question to a point in the soil where the potential is being evaluated. The subscript 1 is used to prevent confusion with z, the vector distance from the origin of coordinates shown in Figure 2. As an example of the use of the form $2q \log_e z_1$, the potential due to the pair of drains in the $m = 0$ column at $n = 2$ is $2q \log_e (z - 4hi) - 2q \log_e [z - (4h + 2d)i] = 2q \log_e \{(z - 4hi/[z - (4h + 2d)i]\}$.

Derivation of potentials and drain flux for wide spacing of drains--The potential due to the column at $m = 0$ is first obtained. With this result at hand the potential for the columns can with reference to Figure 2 be written down by inspection.

The potential in the column $m = 0$ is considered as consisting of two parts: a part C due to the pairs of drains (see Fig. 2) at $n = 0, 2, -2, 4, -4, \ldots$; and a part D due to the pairs of drains at $n = 1, -1, 3, -3, 5, -5, \ldots$. Thus making use of the infinite product forms of the sine and cosine [see, for example, BROMWICH, 1942, p. 213; or PEIRCE, 1929, formulas 816, 817].

$$\begin{aligned} C = 2q\,[&\log_e z/(z - 2di) \\ &+ \log_e (z - 4hi)/(z - 4hi - 2di) \\ &+ \log_e (z + 4hi)/(z + 4hi - 2di) + \ldots] \end{aligned}$$

$$C = 2q \log_e [z/(z - 2di)][(z - 4hi)/(z - 4hi - 2di)]$$

$$[(z + 4hi)/(z + 4hi - 2di)]\ldots = 2q \log_e (\sin \pi z/4hi)/\sin \pi(z - 2di)/4hi$$

and

$$D = -2q \log_e [(z - hi)/(z - 2hi - 2di)][(z + 2hi)/(z - 2hi - 2di)]$$

$$[(z - 6hi)/(z - 6hi - 2di)][(z + 6hi)/(z + 6hi - 2di)] \ldots$$

$$D = -2q \log_e (\cos \pi z/4hi)/\cos \pi (z - 2di)/4hi$$

The complex potential w_0 due to all the drains in the single column $m = 0$, is then

$$w_0 = C + D = 2q \log_e (\tan \pi z/4hi)/\tan \pi (z - 2di)/4hi$$

and the potential w, obtained by summing, due to all the columns is

$$w = 2q \sum_{m=-\infty}^{\infty} \log_e [\tan \pi (z - ma)/4hi]/\tan \pi (z - ma - 2di)/4hi$$

This is an elegant form, but it is not as simple as it appears, for it must be broken down into its real and imaginary parts to be of use in calculations. The separation may be accomplished as follows. Taking ϕ as the real part and $i\psi$ as the imaginary; substituting $x + iy$ for z; and adding a complex constant $(C_1 + C_2 i)$

$$w = \phi + i\psi = 2q \sum_{m=-\infty}^{\infty} \log_e \left(\left\{ \tan \pi [-y + (x - ma)i]/4h \right\} / \right.$$

$$\left. \tan \pi [-y + 2d + (x - ma)i]/4h \right) + C_1 + C_2 i$$

Or writing

$$A = -\pi y/2h, \; B = \pi (x - ma)/2h, \; C = -\pi (y - 2d)/2h \ldots\ldots\ldots\ldots \tag{2}$$

$$w = \phi + i\psi = 2q \sum_{m=-\infty}^{\infty} \log_e \left\{ \tan [(A + Bi)/2]/\tan (C + Bi)/2 \right\} + C_1 + C_2 i \ldots\ldots \tag{3}$$

Now in general for any quantity a

$$\log_e \tan a/2 = \log_e (\sin a/2)/\cos a/2 = \log_e (\sin a/2)/\sin (\pi/2 - a/2)$$

$$= (1/2) \log_e (\sin^2 a/2)/\sin^2 (\pi/2 - a/2)$$

$$= (1/2) \log_e (1 - \cos a)/[1 - \cos (\pi - a)]$$

$$= (1/2) \log_e (\operatorname{vers} a)/\operatorname{vers} (\pi - a)$$

Therefore

$$\log_e \tan (A + Bi)/2 = (1/2) \log_e \operatorname{vers} (A + Bi)/ \operatorname{vers} [\pi - (A + Bi)]$$

or

$$\log_e \tan (A + Bi)/2 = (1/2) \left\{ \log_e \operatorname{vers} (A + Bi) - \log_e \operatorname{vers} [\pi - (A + Bi)] \right\}$$

so that using the following result [KIRKHAM, 1945a, appendix] (in (1) of this reference an equal sign should precede $\log_e \operatorname{vers} (A + Bi)$; and in (3), B and A should be interchanged

$$\log_e \operatorname{vers} (A + Bi) = \log_e (\cosh B - \cos A) + 2i \tan^{-1} [(\tanh B/2)(\cot A/2)] \ldots\ldots \tag{4}$$

there results, remembering that $\cos (\pi - A) = -\cos A$, and that $\cot (\pi/2 - A/2) = \tan A/2$

$$\log_e \tan (A + Bi)/2 = (1/2) \left\{ \log_e (\cosh B - \cos A) - \log_e (\cosh B + \cos A) \right.$$

$$\left. + 2i \tan^{-1} [(\tanh B/2)(\cot A/2)] - 2i \tan^{-1} [(\tanh B/2)(\tan A/2)] \right\} \ldots \tag{5}$$

with a similar expression for $\log_e [\tan (C + Bi)/2]$. From (2), (3), and (5) there results for the potential function

$$\phi = q \sum_{m=-\infty}^{\infty} \log_e \left\{ [\cosh \pi (x - ma)/2h - \cos \pi y/2h]/[\cosh \pi (x - ma)/2h + \cos \pi y/2h] \right\}$$

$$\left\{ [\cosh \pi (x - ma)/2h + \cos \pi (y - 2d)/2h]/[\cosh \pi (x - ma)/ \right.$$

$$\left. 2h - \cos \pi (y - 2d)/2h] \right\} + C_1 \ldots\ldots\ldots\ldots \tag{6}$$

where it will be shown in (8) that

$$C_1 = p_A/\gamma g + t + d \dots\dots\dots\dots\dots\dots\dots\dots \text{(6a)}$$

and for the stream function

$$\begin{aligned}\psi = 2q \sum_{m=-\infty}^{\infty} \Big\{ &- \tan^{-1}\left[\tanh \pi(x - ma)/4h \cdot \cot \pi y/4h\right] \\ &+ \tan^{-1}\left[\tanh \pi(x - ma)/4h \cdot \tan \pi y/4h\right] \\ &- \tan^{-1}\left[\tanh \pi(x - ma)/4h \cdot \cot \pi(2d - y)/4h\right] \\ &+ \tan^{-1}\left[\tanh \pi(x - ma)/4h \cdot \tan \pi(2d - y)/4h\right]\Big\} + C_2\end{aligned}$$

The last equation may be simplified. This is done by noting that the right hand member consists of terms R of the form

$$R = \tan^{-1}(\tanh A \cdot \tan B) - \tan^{-1}(\tanh A \cdot \cot B)$$

which with the aid of PEIRCE'S [1929, formulas 648 and 665] Tables reduce to the form

$$\begin{aligned}R &= \tan^{-1}\left[(\tanh A)/(1 + \tanh^2 A)\right](\tan B - \cot B) \\ &= \tan^{-1}\left[(1/2)(\tanh 2A)(\tan B - \cot B)\right]\end{aligned}$$

or, since [PEIRCE, 1929, formulas 570, 579, 584] $(\tan B - \cot B) = -2 \cot 2B$, R reduces further to the form

$$R = -\tan^{-1}(\tanh 2A \cdot \cot 2B)$$

Using this result ψ becomes

$$\begin{aligned}\psi = -2q \sum_{m=-\infty}^{\infty} \Big(&\tan^{-1}\left\{\left[\tanh \pi(x - ma)/2h\right](\cot \pi y/2h)\right\} \\ &+ \tan^{-1}\left\{\left[\tanh \pi(x - ma)/2h\right]\left[\cot \pi(2d - y)/2h\right]\right\}\Big) + C_2 \dots\dots\dots \text{(7)}\end{aligned}$$

The constant C_2 may be taken equal to zero, since only the difference in successive streamlines is of importance, this difference being proportional to the amount of water passing between them. The constant C_1 is evaluated by means of Condition (I) and Equation (6) with the result, since the Σ in (6) is zero when $y = d$

$$C_1 = p_A/\gamma g + t + d \dots\dots\dots\dots\dots\dots\dots\dots \text{(8)}$$

The flux coefficient q remains to be determined. From Condition (II) and Equations (6) and (8)

$$\begin{aligned}p_A/\gamma g + r = q \sum_{m=-\infty}^{\infty} \log_e \Big(&\left\{\left[\cosh \pi ma/2h - \cos \pi r/2h\right]/\left[\cosh \pi ma/2h + \cos \pi r/2h\right]\right\} \\ &\left\{\left[\cosh \pi ma/2h + \cos \pi(2d - r)/2h\right]/\left[\cosh \pi ma/2h - \cos \pi(2d - r)/2h\right]\right\}\Big) \\ &+ p_A/\gamma g + t + d\end{aligned}$$

That is, introducing the symbol F for brevity

$$q = -(t + d - r)/F \dots\dots\dots\dots\dots\dots\dots\dots \text{(9)}$$

where

$$\begin{aligned}F = \sum_{m=-\infty}^{\infty} \log_e &\left\{\left[\cosh \pi ma/2h - \cos \pi r/2h\right]/\left[\cosh \pi ma/2h + \cos \pi r/2h\right]\right\} \\ &\left\{\left[\cosh \pi ma/2h + \cos \pi(2d - r)/2h\right]/\left[\cosh \pi ma/2h - \cos \pi(2d - r)/2h\right]\right\}\end{aligned}$$

This expression may be simplified by sorting out the m = 0 term; by making use of the identity $(1 - \cos A)/(1 + \cos A) = \tan^2 A/2$, and its reciprocal; and by noting that contributions from columns having the same absolute value of m are the same. Also, in order to keep the arguments of the logarithms greater than unity, a minus sign is introduced before the Σ, and the ratios in the braces under the logarithm are inverted. Performing these operations

$$F = -2 \Big(\log_e [\tan \pi(2d - r)/4h]/(\tan \pi r/4h) + \sum_{m=1}^{\infty} \log_e \Big\{ [\cosh \pi ma/2h + \cos \pi r/2h]/[\cosh \pi ma/2h - \cos \pi r/2h] \Big\} \Big\{ [\cosh \pi ma/2h - \cos \pi(2d - r)/2h]/[(\cosh \pi ma/2h + \cos \pi(2d - r)/2h] \Big\} \Big) \quad \ldots . (10)$$

Computation of the drain flux--In order to compute the quantity of water Q flowing into unit length of drain per unit time, it is assumed that the radius of the drain is small compared to the distance to adjacent boundaries, that is, it is assumed that $r \ll h, h - d, d, a$. In this event, from (6), provided y and x are taken of the same order of size as r, $\phi = q \log_e (\cosh 2\pi y/a - \cos 2\pi x/a)$ + terms which are approximately constant or making use of the expansions

$$\cosh a = 1 + a^2/2! + \ldots, \quad \cos a = 1 - a^2/2! + \ldots$$

$$\phi = q \log_e [(2\pi y/a)^2 + (2\pi x/a)^2] + \text{const., approx.}$$

that is, if r_1 is the radial distance from the drain axis to the point in the soil whose cartesian coordinates are (x, y)

$$\phi = q \log_e (2\pi/a)^2 r_1{}^2 + \text{const., approx.}$$

$$= 2q \log_e r_1 + \text{const., approx.}$$

The drain flux is therefore

$$Q = K \cdot 2\pi r \, [\partial\phi/\partial r]_{(r_1 = r)} = 4\pi q K$$

or in terms of the original parameters of the problem, Figure 1, the drain flux is, from (9) and (10)

$$Q = 2\pi K (t + d - r) / \Big\{ \log_e [\tan \pi(2d - r)/4h]/(\tan \pi r/4h) + \sum_{m=1}^{\infty} \log_e [(\cosh \pi ma/2h + \cos \pi r/2h)/(\cosh \pi ma/2h - \cos \pi r/2h)] [\cosh \pi ma/2h - \cos \pi(2d - r)/2h]/[\cosh \pi ma/2h + \cos \pi(2d - r)/2h] \Big\} \quad \ldots . . (11)$$

If a, the drain spacing, becomes very large

$$Q\,(a \to \infty) = 2\pi K (t + d - r) / \Big\{ \log_e [\tan \pi(2d - r)/4h]/(\tan \pi r/4h) \Big\} \ldots \ldots . (11a)$$

an expression independent of the spacing.

If in (11a) h is very large compared to (2d - r), $\tan \pi(2d - r)/4h = \pi(2d - r)/4h$ and $\tan \pi r/4h = \pi r/4h$ so that

$$Q\,(a \to \infty, h \to \infty) = 2\pi K (t + d - r)/ \log_e (2d - r)/r \ldots \ldots \ldots \ldots (11b)$$

The expression for drain flux, (11), agrees with that previously given by **KIRKHAM** [1940b], if it is noted that t was taken as zero, r was neglected compared to d, and a was taken large compared to d, (h - d), and 2d so that the Σ term was negligible.

Derivation of potentials and drain flux for close spacing of drains--The basic result needed here can be taken from **KIRKHAM** [1945a]. There it was shown that the complex potential w_0 due to a row of tubes at y = 0 is

$$w_0 = q \log_e \operatorname{vers} 2\pi z/a$$

a being the spacing between the drains and $z = x + iy$, with $i = (-1)^{1/2}$; the origin of coordinates is taken on the axis of one of the drains, y being vertical upward. From this result, and inspection of

Figure 1, the complex potential due to all the rows may be written down immediately. It is:

$$w_a = q_a \sum_{n=-\infty}^{\infty} (-1)^n \log_e [\text{vers } 2\pi(z - 2nhi)/a]/[\text{vers } 2\pi(z' - 2nhi)a] + C_3 + iC_4 \quad \ldots \; (12)$$

where for brevity z' is set equal to $z - 2di$; C_3 and C_4 are constants and the subscript a is used to designate quantities alternate to those previously obtained.

Taking $w_a = \phi_a + i\psi_a$ and using (4) with (12),

$$\phi_a = q_a \sum_{n=-\infty}^{\infty} (-1)^n \log_e [\cosh 2\pi(y - 2nh)/a - \cos 2\pi x/a]/$$

$$[\cosh 2\pi(y - 2d - 2nh)/a - \cos 2\pi x/a] + C_3 \quad \ldots\ldots\ldots\ldots \; (13)$$

where from Condition (I) and Equation (13) it is seen that

$$C_3 = p_A/\gamma g + t + d \quad \ldots\ldots\ldots\ldots \; (13a)$$

and

$$\psi_a = 2q_a \sum_{n=-\infty}^{\infty} (-1)^n \left\{ \tan^{-1} [\tanh \pi(y - 2nh)/a \cdot \cot \pi x/a] \right.$$

$$\left. - \tan^{-1} [\tanh \pi(y - 2d - 2nh)/a \cdot \cot \pi x/a] \right\} + C_4 \quad \ldots\ldots\ldots\ldots \; (14)$$

where C_4 may be taken equal to zero,

As before, Boundary Condition (II) is used to evaluate q_a, whence Q_a, the alternate expression for the flow rate into unit length of drain, is $Q_a = 4\pi K q_a$. Thus from Condition (II) and Equations (13) and (13a), and making use of the identities $\cosh A - 1 = 2 \sinh^2 A/2$, and $\sinh (A - B) \cdot \sinh (A + B) = \sinh^2 A - \sinh^2 B$

$$Q_a = 2\pi K (t + d - r)/\left\{ \log_e [\sinh \pi(2d - r)/a]/\sinh \pi r/a \right.$$

$$\left. - \sum_{n=1}^{\infty} (-1)^n \log_e (\sinh^2 2\pi nh/a - \sinh^2 \pi r/a)/[\sinh^2 2\pi nh/a - \sinh^2 \pi(2d - r)/a] \right\}. \; (15)$$

which agrees with a previous result by **KIRKHAM** [1940a], since t was there taken equal to zero, and r was neglected compared with d, 2d, h, h - d, and larger quantities.

When h approaches ∞, that is, if the impermeable layer is at great depth, the summation in (15) vanishes and the expression for drain flux simplifies to

$$Q_a (h \to \infty) = 2\pi K (t + d - r)/\left\{ \log_e [\sinh \pi(2d - r)/a]/\sinh \pi r/a \right\} \quad \ldots\ldots \; (15a)$$

An infinite number of terms would be required in (11) to obtain the same result.

If in (15a) the drain spacing is very large compared to $2d - r$ then $\sinh \pi(2d - r)/a = \pi(2d - r)/a$ and $\sinh \pi r/a = \pi r/a$ so that

$$Q_a (h \to \infty, a \to \infty) = 2\pi K (t + d - r)/[\log_e (2d - r)/r] \quad \ldots\ldots\ldots\ldots \; (15b)$$

an expression independent of both spacing and depth to impermeable layer. This last equation agrees with (11b) as it should.

If in (15b) $d \to r$, that is, if the top of the drain tube approaches the soil surface $(2d - r)/r \to 1$, $\log_e (2d - r)/r \to 0$ and $Q_a \to \infty$. This is the result to be expected, because with no soil above the drain tube there would be a path of zero resistance for the ponded water into the drain tube. (The analysis here tacitly assumes that the "permeability" of water is infinite, and that t is greater than zero).

Rate of intake at the soil surface--The rate of intake Q' or Q'_a of water at the soil surface per unit area is obtained by differentiating ϕ or ϕ_a with respect to y, evaluating the result at $y = d$, and multiplying the result by K. Thus, from (6) and (13), and remembering that $Q = 4\pi qK$, $Q_a = 4\pi q_a K$, it is found that the two expressions for water intake per unit area at the surface of the soil are

$$Q' \equiv K\,(\partial\phi/\partial y)_{y\,=\,d} = (Q/2h)(\sin \pi d/2h)$$

$$\sum_{m\,=\,-\infty}^{\infty} \left[\cosh \pi(x - ma)/2h\right]/\left[\cosh^2 \pi(x - ma)/2h - \cos^2 \pi d/2h\right] \quad \ldots\ldots (16)$$

$$Q'_a = K\,(\partial\phi_a/\partial y)_{y\,=\,d} = (Q_a/2a) \sum_{n\,=\,-\infty}^{\infty} (-1)^n$$

$$\Big\{\left[\sinh 2\pi(d - 2nh)/a\right]/\left[\cosh 2\pi(d - 2nh)/a - \cos 2\pi x/a\right]$$

$$+ \left[\sinh 2\pi(d + 2nh)/a\right]/\left[\cosh 2\pi(d + 2nh)/a - \cos 2\pi x/a\right]\Big\} \quad \ldots\ldots\ldots (17)$$

Before performing the differentiation indicated in (16) and (17), it is convenient to write $\log_e A/B = \log_e A - \log_e B$, etc.

A numerical check--The alternate potentials and drain flux expressions are identical in value with those already obtained. Thus, referring to (6) and (6a) and (11) and (15), $\phi = \phi_a$ and $Q = Q_a$. Furthermore, the alternate stream functions (7) and (14) will be identical to within a constant ($C_2 - C_4 = 2\pi q$). As a numerical check we test the identity $Q = Q_a$.

Denoting the denominator of (11) by L and the denominator of (15) by L_a, there must result, if the analysis is correct

$$L = L_a$$

To test this supposed identity the following convenient numerical values are used: $r = 1/4$, $d = 4 + 1/8$, $2d = 8 + 1/4$, $2d - r = 8$, $h = 16$, $a = 32$. Accordingly

$$L = \log_e (\tan \pi/8)/(\tan \pi/256) + \sum_{m\,=\,1}^{\infty} \log_e \Big\{\left[\cosh m\pi + \cos \pi/128\right]/\left[\cosh m - \cos \pi/128\right]\Big\}$$

$$\Big\{\left[\cosh m\pi - \cos \pi/4\right]/\left[\cosh m\pi + \cos \pi/4\right]\Big\}$$

$$L_a = \log_e (\sinh \pi/4)/(\sinh \pi/128) - \sum_{n\,=\,1}^{\infty} (-1)^n \log_e \left[(\sinh^2 n\pi - \sinh^2 \pi/128)/(\sinh^2 n\pi - \sinh^2 \pi/4)\right]$$

Performing the calculations it is found that

$$L = 3.519028 + 0.050751 + 0.002188 + 0.000093 + 0.000005 = 3.57207 \text{ to five decimals}$$

and

$$L_a = 3.566406 + 0.005678 - 0.000011 = 3.57207 \text{ to five decimals}$$

In the above expressions the numbers after the leading term correspond to values of $m = 1, 2, 3,$ and 4, and to $n = 1$ and 2. For the example chosen it is seen that the leading term gives the correct result to good approximation in both cases. The leading term in L_a gives the correct result to three significant figures.

Also it is noticed that since L and L_a are both derived from ϕ and ϕ_a, (L and L_a are just twice the value of the summation in (6) and (13) respectively, when there y is set equal to r, and x equal to zero) the above numerical calculation serves as a check on the alternate expressions for the potential.

Tables for numerical calculations--Although logarithmic, trigonometric, and hyperbolic functions are extensively tabulated, a few remarks concerning tables may still be in order, as in most cases tables of logarithmic functions are given to base ten and of trigonometric functions in degrees, minutes, and seconds of arc, conversions being required to natural logarithms and to radians for use in the formulas presented here. Since the beginning of World War II extensive tables of natural logarithms and trigonometric functions for radian argument as well as extensive tables of hyperbolic functions have appeared. These tables obviate conversions and interpolations for a number of significant figures. The tables referred to are those of the MATHEMATICAL TABLES PROJECT [1941-1943]. (A complete list of presently completed tables of the Mathematical Tables Project and a short review of them is given by BROWN [1947].)

For the calculations in the present paper, except for those in the numerical check just given, where use was made of the Tables of the MATHEMATICAL TABLES PROJECT [1939-1943], PEIRCE'S [1929] Tables, and CAMPBELL'S [1929] Tables were used. The latter small book of

75 pages is preferred, as it has one more significant figure in the arguments than does Peirce's Tables, interpolations therefore not being required in slide-rule work.

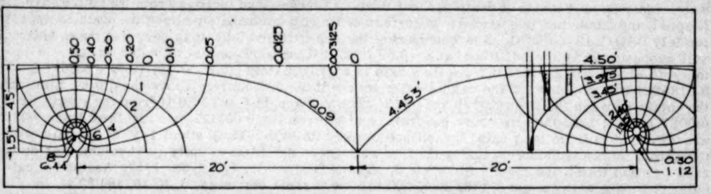

Fig. 3--Streamlines and equipotentials for flow into equally spaced drains 40 ft apart and 4.5 ft deep in soil overlying an impervious layer at six feet depth; in the left hand half of the figure the equipotentials are in arbitrary units; in the right hand half the equipotentials are given in feet of hydraulic head referred to a horizontal plane through a drain axis; the piezometers show the head of water, 3.975 ft, on the 3.975 ft equipotential

Results and discussion--Some results of the analysis are depicted graphically in the figures. Figure 3 shows the potential function and stream function for a drain spacing of 40 ft, a drain depth of 4.5 ft, and a drain diameter of about one foot. The figure thus corresponds to one of the streamline patterns previously obtained experimentally and pictured [KIRKHAM, 1940b]. In this reference streamlines are plotted on the experimental patterns but the equipotentials are not given. The equipotentials (8, 6.44, 6, etc.) on the left hand half of Figure 3 are graphs of y versus x of (6) with q taken equal to -1 and $C_1 = 0$. The values of q and C_1 are chosen for convenience and do not agree with the values given in (6a), (9), and (10). This may for the moment be considered immaterial, as the interesting feature in equipotential plots is generally considered to be the difference in potential values, a consequence of the flow rate being directly proportional to the space rate of change of potential. For example, the crowding of the equipotentials near the drains indicates a rapid rate of flow there.

Although it is generally convenient to plot equipotentials in arbitrary units, it is worth while here to convert these values to actual units of hydraulic head, for the reason that hydraulic head is the physical quantity of interest and a measurable one. The conversions have been made on the right hand side of Figure 3, the level of the axes of the drains being the reference level. The conversions are accomplished with the aid of the equation $\phi_R = (-0.525\phi_L + 4.50)$ ft, where ϕ_R is the value of an equipotential curve on the right hand side, and ϕ_L the corresponding value on the left. The latter equation is obtained by setting $\phi_R = -A\phi_L + B$ and determining A and B from the conditions of Figure 3 : that when $\phi_R = 0.30$ ft, $\phi_L = 8$; and that when $\phi_R = 4.50$ ft, $\phi_L = 0$. The values of ϕ_R can also be obtained directly from (6), (6a), (9), and (10) by putting $d = 4.5$, $r = 0.30$, $h = 6$, $a = 40$, $t = 0$, and $p_A = 0$ (gage pressure). The constant difference between the equipotentials 8, 6, 4, 2, and 0 is 2; the constant difference in hydraulic head between the equipotentials 0.30, 1.35, 2.40, 3.45, and 4.50 is 1.05 ft.

Since q in (6) does not involve the soil permeability, but is purely a geometric quantity, the equipotentials (the lines of equal hydraulic head) do not involve the soil permeability, providing the soil permeability is constant. For example, if a sandy soil overlies an impervious layer at one location and a silt loam soil overlies and impervious layer at another, and if each soil has drains installed with the geometry shown in Figure 3, say, then the distribution of hydraulic head throughout these soils will be the same. The streamlines (presently to be discussed) will also have the same geometric distribution, but the amount of flow passing between a pair of lines in the sandy soil will be greater than for the same pair in the silt loam. On the right hand side of Figure 3, three standpipes (piezometers) are shown with water standing in them at its equilibrium level. Although the pipes are at different depths and different distances from the drain, the water level is the same in each of them because the end of each is on the same equipotential. It would of course be erroneous to believe that the water in the standpipe at the left would be at a level below the drain outlet, on the basis that the drain "sucks in" water from below it. Pressure drives water into the drains, not suction. To add a homely example, pressure drives lemonade through a straw to the mouth.

Water intake at the soil surface--The streamlines 0.5, 0.4, 0.3, ... in Figure 3 are plots of y versus x in (7) with, for convenience, C_2 taken equal to $2\pi q$ and q equal to $1/4\pi$. The significant feature of streamlines is that the difference between designating numbers of any pair of lines is proportional to the amount of flow between them. This feature in Figure 3 enables one to determine the rate of intake of water at the soil surface, at various distances from the drain. Thus the quantity of water per unit time flowing between the lines 0.5 and 0.4 is 0.1Q, where Q, as already defined, is the total quantity of water entering unit length of drain per unit time. As these lines (scaling from the figure) are 1.12 ft apart, the intake per unit area at the surface of the soil immediately above the drain is approximately 0.1Q/1.12 = 0.089Q. Now considering the lines 0.1 and 0.05, it is seen that these enter the soil respectively at x = 6.81 ft and at x = 9.50 ft so that the surface rate of water intake at a distance (6.81 + 9.50)/2 = 8.15 ft from the y axis is approximately [(0.1 - 0.05)/(9.50 - 6.80)] Q = 0.0185Q. This is about 1/5 the rate of water intake at the soil surface above the drain. Similarly the intake between the lines 0.0125 and 0.003125, which are 14.5 and 18.0 ft from the y axis, is 0.0027Q, about 1/33 the rate above the drain; and between the 0.003125-line and the 0 lines, which are 18 and 20 ft from the y axis, the surface intake rate is 0.00156Q, about 1/57 of the rate above the drain. In round numbers, taking the flow rate above the drain as unity (unit volume per unit area per unit time), the results for x = 0, 8, 16, and 20 ft are 1, 1/5, 1/33, 1/57. Analytical calculations made with the aid of (16) show that for these same distances, 0, 8, 16, and 20 ft, the ratios are 1, 1/4.77, 1/34.5, and 1/55.3 (0.0904Q being the surface inflow rate immediately above the drain). These analytical results verify the validity of the graphical method.

Two more cases for surface inflow rate are considered: (1) The geometry is as in Figure 3, except that a = 100 ft. Here the results (obtained with the aid of (16)) for the ratio of intake at x = x to that at x = 0, for x = 0, 8, 16, 20, 40, and 50 ft are respectively 1, 1/4.77, 1/34.5, 1/110.5, 1/20,800, and 1/143,400 (0.0902Q being the surface inflow rate immediately above the drain). (2) The geometry is as in Figure 3, except that a is 100 ft and h is infinite. Here the results (from (17), only the n = 0 term being required) for x = 0, 8, 16, 20, 40, and 50 ft are respectively 1, 1/4.07, 1/12.45, 1/18.16, 1/45.8, and 1/50.7 (0.0712Q being the surface flow rate immediately above the drain). Upon comparing the last two cases the tremendous effect of the impervious layer in cutting down the flow rate at a distance from drains, at spacings ordinarily used, is evident. These results are of interest in the problem of leaching undesired salts into drains from soils by flooding the affected areas, and in the problem of leaching away desired nutrients. The results show that if a true impervious layer exists, a small distance below the drains, the amount of leaching midway between the drains will be effectively nil. On the other hand, the results show that the leaching of nutrients immediately above drain lines occurs at a relatively rapid rate. It may be remarked that artesian pressure will produce the same effect as an impervious layer. In this latter regard one may compare Figure 1b in a paper by HARDING and WOOD [1941], where upward flow produces a nearly horizontal streamline (stream surface), the equivalent of a horizontal barrier to downward flow. In practice one may utilize piezometers to determine the direction of and relative rates of flow in seepage problems [CHRISTIANSEN, 1943]. Leaching midway between drains may be increased by successive floodings of a field with time being allowed for the water table to fall below the surface between floodings. If this is done (because of a depression developing in the water table over the drains) a horizontal component of flow develops to aid the vertical velocity component in the removal of water from the area between the drains.

Figure 4 shows, graphically, Q' the inflow rate per unit area at the soil surface for the two cases considered in the last paragraph with the soil permeability taken at one inch per day. The maximum flux density shown is 0.0477 cu ft/sq ft/day. This is the equivalent of a seepage rate of 0.0477 × 12 = 0.572 inches per day. It is interesting in studying this figure to note that if instead of drains at 4 1/2 ft depth, there were a layer of coarse sand or gravel at 4 1/2 ft depth, extending to infinity in all horizontal directions under the soil, and draining freely at atmospheric pressure, the seepage would be increased, and for each square foot of surface area, to 1.0 inches per day. This result follows from the assumption that the soil permeability is one inch per day, and from the fact that by definition the soil permeability is the rate of free seepage of water under the action of gravity, as in the latter case. It is apparent that tube drains are not at all as satisfactory as a drained layer of sand beneath a soil. If an undrained layer of sand exists below the soil, the place for the drains is in the sand, even if the sand is at somewhat greater depth than drains would ordinarily be placed.

A practical aspect of Figure 4 is the need of eliminating depressed areas between drains in soils of low permeability and where it is not feasible to remove surface water by surface drains. Figure 5 shows two fields with drains installed at the same depth and spacing. In A, ponded water will flow into the soil relatively rapidly since the water enters the soil immediately above the drains, where Figure 4 shows the surface inflow rate to be a sharp maximum. In B, the ponded water will enter the soil at a relatively extremely low rate, particularly if there is a hardpan layer just below the drains. With regard to a practical method for establishing the type of surface drainage shown in Figure 5A, use might be made of the Whirlwind Terracer recently developed at Iowa

State College. The results might also be accomplished by plowing, dead furrows to be left over the drains. Independent of, or in addition to these procedures, effort should be made, through suitable agronomic practices, to attain and maintain the upper six inches or more of the surface soil in a high state of permeability. Drainage would then effectively occur after the manner indicated in Figure 5A.

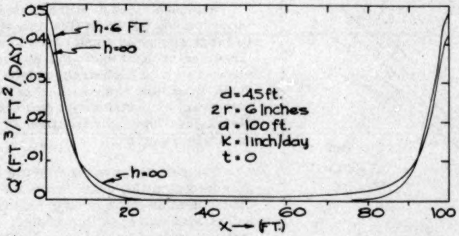

Fig. 4--Inflow rate per unit area Q' at the surface of the soil as a function of distance from a vertical plane through a drain axis; in both curves, depth to the center of drain d is 4.5 ft; drain diameter 2r, six inches; drain spacing a, 100 ft; thickness of ponded water t, zero (an infinitesimally thin layer); and soil permeability K is one inch per day; for the initially higher curve, the depth to the impervious layer h is six feet, for the initially lower curve,∞; multiply the ordinates by $[1 + t/(d - r)]$ to obtain Q' when the thickness of ponded water is t

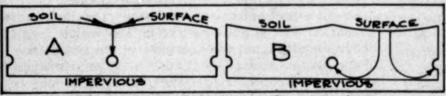

Fig. 5--Effect of ground contour on flow into drains

Effect of drain depth and drain diameter on drain flux--The effect of the several parameters d, r, a, h, t, and K on the drain flux Q will now be considered. In Figure 6 graphs of drain flux versus drain depth are given for drains of diameter 4, 6, 8, and 12 inches, for a soil of permeability one inch per day. For all values of drain diameter the depth of ponded water is taken as zero, and the drain spacing and the depth to the impervious layer, infinity. Depths of the drain tubes refer to the depth of the bottom of the drains, that is, to the depth of trench required for installing the drains. The figure illustrates a number of features. The drain intake increases approximately linearly with depth, the increase being somewhat greater at the smaller depths than at the larger. The remarkable feature of the curves is the relatively unimportant effect of the drain size on the flow rate. For example, at two feet depth ($d + r$ = two feet), increasing the drain size from four-inch diameter to six-inch, eight-inch, and 12-inch diameters, increases the drain flux, respectively from 0.287 to 0.306 to 0.317 to 0.325 cu ft per day per ft length of drain. The corresponding percentage increases referred to the two-foot depth are only 6.6 per cent, 10.5 per cent, and 13-3 per cent. These values may be compared with the increases obtained at 12 ft depth when the drain sizes are increased, the respective figures being 8, 14, and 23 per cent, still relatively small values compared with the drain size increases of 50 per cent, 100 per cent, and 200 per cent.

The above values are based on the assumption that the drain in each case is running full with no back pressure. If the drains are running nearly empty, the above increases will be larger, but they will still be relatively small. Calculations show that at four-foot depth ($d + r = 4$), an increase in the drain diameter of 400 per cent (three inches to 12 inches) increases the flow 20 per cent when the drains are running full and 50 per cent when running nearly empty. The latter value is obtained by substituting $+r$ for $-r$ in (11b), with $d + r$ = four feet.

The presence of an impervious layer near the drain has little effect on the role of drain size in influencing drain intake. For example, calculations (made with the aid of (11a) show that with drains at two-foot depth and an impervious layer two feet below the bottom of the drains, an increase in the drain diameter from four inches to 12 inches (300 per cent) increases the drain flux from 0.271 to 0.310 (14.4 per cent), as compared with a change from 0.287 to 0.325 (13 per cent) when the impervious layer is at infinity. The corresponding figures for drains at 14 ft depth are

1.014 to 1.224 (20.7 per cent) with impervious layer two feet below the drains; 1.233 to 1.510 (22.5 per cent) with impervious layer at infinity. The presence of the impervious layer cuts down the drain flux, but has little effect on drain size as a factor in controlling flow to the drains.

Although the size of the drain has small effect in increasing the drain flux, this effect may still be large enough in some cases to make the use of large drains desirable. For example, Figure 6 shows that a 12-inch drain installed at nine-foot depth drains the same amount of water as an eight-inch drain at 10-foot depth or a six-inch drain at 10 1/2-foot depth. Installations of drains at these depths is uncommon.

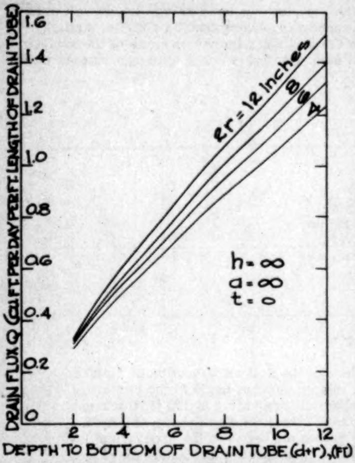

Fig. 6--Drain tube inflow Q as a function of depth $d + r$ to bottom of drain, with drain diameter $2r$ as parameter; drain spacing a is ∞; depth to impervious layer h is ∞; soil permeability K, assumed uniform from soil surface to a great depth (∞), is one inch per day; thickness of ponded water t is zero; inflow will decrease if the depth to the impervious layer becomes finite; effect of drain spacing is negligible for spacings ordinarily used (see Fig. 8); multiply the ordinates by $[1 + t/(d-r)]$ to obtain flow when thickness of ponded water is not zero

The relatively small effect of the drain diameter in controlling drain intake merits further discussion, as there is an erroneous viewpoint prevalent with regard to this matter. It is reasoned that the drain diameter is a "bottle neck" in a drainage system and that doubling the drain radius, with the attendant doubling of the intake area, will at least double the inflow rate and hence the effectiveness of the drainage system. The fallacy in this argument stems from a lack of recognition of the fact that when the drain radius is increased (with the attendant larger area for inflow) the density of fluid flow at the entrance to the drain is decreased by an almost proportionate amount, the over-all effect being that the inflow remains nearly constant. The slight increase in flow which does occur results from the decrease in the resistance of the system caused by its decrease in size when the larger drain is used. The above points may be brought out simply and without use of mathematics by considering the radial flow system shown in Figure 7. In this system, because of symmetry, only a sector, 0AB, with fixed external diameter 0A and variable internal diameters such as 0I, 0G, and 0E, need be considered. Assuming that the difference in hydraulic head between AB and the drain is maintained constant, the flow entering IJ will be the same as will enter a larger drain GH, except that in the latter case there will be a small increase due to the decrease in friction of the system resulting from the removal of the section of soil GHIJ. Doubling the drain diameter will not halve the friction. Actually the friction of a section such as EFGH varies directly as the length HF and inversely as the length of the arc EF which is presented to the flow. As successive sections such as EFGH and CDEF, are removed, proceeding outward from the center, the length of arc, such as GH, EF, and CD increases, these increases making the decreases in friction resulting from the removal of the successive sections larger, say, than in a linear flow system; but if the radius, such as 0I and 0G of the sectors removed is small compared to the radius 0A, the successive decreases in friction will be small compared to the total friction. It may easily be shown that the total resistance of a radial flow system varies directly as the logarithm of the ratio of the external to internal radius of the system.

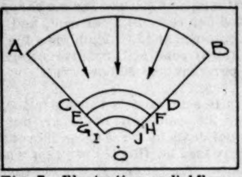

Fig. 7--Illustrating radial flow into a drain

In the above discussion the only item under review has been the size of the drain, insofar as the size affects the ability of the drain to "pull" water from the soil. (With regard to water carrying capacity a five-inch tile drain will carry more than 1 1/2 times as much water as a four-inch tile, and more than 2 2/3 times as much as a three-inch tile.) Furthermore, it is again pointed out, that the above analysis does not consider the constricting effect on water entry at the spaces where the individual tiles butt against each other, the tiles being otherwise impervious to flow. On the contrary, in applying this analysis to tile drain systems it is assumed that the tiles are surrounded by a thin layer of pervious material, as gravel. Eventually the effect of the constricting spaces between individual tiles must be taken into account, and when this is done, the present results will furnish information necessary to compare the effectiveness of tile drains with and without the gravel layer. Many features of the problem remaining to be solved will no doubt be the same as those brought out here. For example, the drain intake will probably vary nearly linearly with depth and approximately logarithmically with width of the space between the individual pieces of tile.

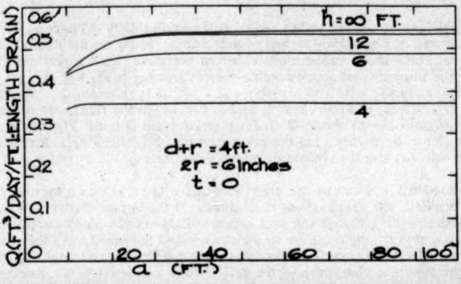

Fig. 8--Drain tube inflow Q as a function of drain spacing a; with depth h of impervious layer as parameter; depth to bottom of drain tube d + r is four feet; drain diameter 2r, six inches; thickness of ponded water t, zero; soil permeability K, one inch per day; depths to the impervious layer are h = ∞, 12, six, and four feet; the figure shows drain inflow to be independent of drain spacing for spacings ordinarily used; and to be dependent on depth to the impervious layer if the drain is close to the impervious layer; multiply the ordinates by $[1 + t/(d - r)]$ to obtain drain inflow when thickness of ponded water is not zero; divide the ordinates by the drain spacing to determine the number of surface inches of water removed per day; multiply the ordinates by 100 if the permeability is 100 inches per day, by ten if the permeability is ten inches per day

Effect of drain spacing and of depth to impervious layer--In Figure 8 the drain depth and drain diameter are held constant, with the drain inflow rate as dependent variable, the drain spacing as independent variable, and the depth of impervious layer as parameter. The depth of the drain bottom $(d + r)$ is kept at four feet and the drain diameter $(2r)$ at six inches. The thickness of ponded water is zero and the soil permeability is one inch per day, the latter two quantities, t and K, being as in Figure 4 and 6. The curves in Figure 8 are plotted for the cases that the drain lies on the impervious layer $(h = 4)$, the impervious layer is two feet below the drain $(h = 6)$, eight feet below the drain $(h = 12)$, and at infinite depth. The flatness of the curves for drain spacings greater than about 20 ft shows that the drain inflow is independent of drain spacing for all spacings ordinarily used. This means that twice as much (not 1.9 or 2.1 times as much) water will be drained from a field having 50 ft spacing of drains as will be drained from one with 100 ft spacing; and four times as much at 25 ft spacing as at 100 ft spacing. This statement is true regardless of how deep an impervious layer may lie, providing the depth of the impervious layer is the same for the whole field.

Although the drain inflow into an individual drain is independent of drain spacing for normal spacings of drains, the inflow is not independent of the depth of impervious layer, unless the layer is several feet below the drain. This is true because the flow lines are more constricted when the drain is next to the impervious layer than when the layer is at a distance. Figure 8 shows that bringing the impervious layer from infinity up to the bottom of the drain reduces the flow 32 per cent. But if the impervious layer is two feet from the drain the reduction would only be ten per cent; thus the effect is noticeable only if the drain is very close to the impervious layer. The question arises as to whether, with fixed depth, from the surface to impervious layer, there would be a position for the drain tube which would result in a maximum flow, and where this position would be. This point was discussed [KIRKHAM, 1940b], where it was shown graphically that for a hardpan layer at six feet and drain diameter of 1/2 ft (thickness of ponded water, zero) the best depth would be for the drain center at about 4 1/2 ft. Analytically the best depth may be obtained by differentiating Q in (11a) with respect to d, setting the result equal to zero and solving for d. The expression yielding best d turns out to be.

$$\log_e [\tan \pi(2d - r)/4h]/(\tan \pi r/4h) = (\pi/h)(t + d - r)/\sin 2\pi(2d - r)/4h$$

which cannot be solved explicitly. A numerical calculation, however, shows that for the conditions given (h = six feet, $r = 0.25$ ft) the best depth for the drain center is 5.02 ft, but the maximum for the Q - d curve [KIRKHAM, 1940b] is not sharp and so the best value of d is not critical. Also it is to be remembered that the theory is only approximate when the drain radius is small compared to the distance of the drain to the impervious layer.

Effect of thickness of ponded water and of soil permeability--There remains to be considered the effect of thickness of ponded water and of soil permeability on the drain flux Q. There need little be said here, since these parameters enter in the theoretical Equations (11) and (15) simply. Let t_1 and t_2 be the thickness of ponded water corresponding to Q_1 and Q_2, all other parameters being the same, then $Q_2/Q_1 = (t_2 + d - r)/(t_1 + d - r)$. If t_1 is zero, $Q_2 = Q_1 (t_2 + d - r)/(d - r) = Q_1 [1 + t_2/(d - r)]$. Thus, in Figures 4, 6, and 8, for which the thickness of ponded water was taken as zero, it is possible to obtain Q′ from Figure 4 and Q from Figures 6 and 8, for a thickness of ponded water t, by multiplying the ordinates by $[1 + t/(d - r)]$. If d is large compared to t, as it generally will be, t will have small effect on Q′ and Q.

The soil permeability K enters the expressions for Q purely as a factor. Therefore, if the permeability is doubled, the drain inflow is doubled. If the permeability is halved, the drain inflow is halved, and so on. Although the soil permeability occurs most simply in the analysis, it is still the most important single factor in the theory and the one giving the most trouble from a practical viewpoint. In the theory it has been assumed that K is constant, but this is not so in practice, since the dynamic character of the soil is also reflected in K. Furthermore, the soil permeability will not be constant in space. Worm holes, root channels, and cracks may cause large local variations in permeability. A gopher hole from the soil surface to a drain may cause more total flow into a drain tile from a flooded soil than all other seepage together. On the other hand, in water logged soils needing draining (it is remembered the results in this paper apply only to water-saturated soils) there will ordinarily be few large structural discontinuities, so that permeability can be characterized and measured. When permeability varies with time, the average value for the time interval under consideration is used in the drainage expressions.

A final point may be mentioned. FLODKVIST [1931] has stated that the soil permeability is much greater immediately over drain tiles than at distances removed from them. He gives as reason, the disturbance made in the soil when the trenches for the tile are dug and believes that such disturbances cause the permeability to remain increased for 20 or more years after the tiles have been installed. There is some question as to the validity of Flodkvist's measurements because of the method of performing them. The tests were made by comparing the time for a certain amount of water to seep into the soil over a drain with the time of seepage at a short distance away from the drain. But Figure 4 shows that one should expect a high infiltration rate just above the drain and considerably less at distances not far away. Nevertheless, marked differences were found in some cases at small distances, indicating that the permeability may have been greater directly over the drains. One way that permeability might be increased near drains is by the washing of particles from the soil by the faster moving soil-water near the drain, when the drains are first installed. If it should turn out (which is doubtful) that the permeability really is very large where the excavation for drains was originally made, then the analysis here can not be used; instead, the space over the drains may be considered as an open ditch insofar as the ground-water flow is concerned. Further measurements on the permeability of soils in the immediate neighborhood of drains should be made.

Time for removal of ponded water--The rate at which the level of ponded water will fall for a condition illustrated in Figure 1 can be determined from the theory. This is illustrated in the following example: Suppose, as is a not uncommon condition in the humid north central states, particularly in May and June, that heavy rains have caused areas to be ponded to a depth of six inches, and that there is no way for this water to escape except through the drain tubes. Suppose that the permeability of a certain soil in question (say a Glencoe silty clay loam) is one inch per day and that this soil has an impervious layer at six-foot depth and has drain tubes six inches in diameter installed at four-foot depth ($d + r$ = four feet) on 100 ft spacings. Then, since the average depth of water during the period that the water stands on the soil is three inches, the average rate at which a foot length of drain tube receives water can be obtained from Figure 8 by multiplying the ordinate (0.488) of the curve for which $h = 6$ by $[1 + t/(d - r)] = [1 + 0.25/(3.75-0.025)] = 1.0715$, the result being $1.0715 \times 0.488 = 0.523$ cu ft per day per ft length of drain. As the drains are spaced at 100 ft, the lowering of the ponded level (ignoring evaporation) is $0.523/100 = 0.00523$ ft per day or 0.0627 inches per day; and it would take $6/0.0627 = 95.6$ days for the six inches of water to seep into the drains. But if another soil in question (say a Tama silt loam) had a permeability of 324 inches per day, all other items being as above, the six inches would seep into the drains in $95.6/324 = 0.295$ days. If the drain spacings were reduced to 50 ft, the times would be 47.8 and 0.1485 days for the two soils; and if cut to 25 ft, 23.9 and 0.074 days. The results would also be approximately the same (see Fig. 8) if the impervious layer were at great depth instead of six feet and they would also be approximately the same if the drains were 12 inches (or three inches) in diameter instead of six inches, since the effect of drain diameter or drain intake, as has been emphasized, is small. It is obvious that in soils of low permeability, surface water should be removed by surface drains. The general formula for the time T to remove water of thickness t from a field where the drain spacing is a is $T = ta/\bar{Q}$ where the bar indicates the average value of Q during the time T of removal. The value $\bar{Q}$ is obtained by substituting $t/2$ for t in (11) or (15).

The time for removal of the ponded water into drain tubes when the soil is underlain with an impervious layer may be compared with the time required when the soil is underlain with a horizontal stratum of gravel draining freely to an exit at atmospheric pressure. The above two cases are considered with the modification that instead of the drains at four-foot depth there is the horizontal stratum of gravel. For the soil permeability one inch per day, the water level in the case of the gravel layer would fall the six inches in six days; and for the soil of permeability 324 inches per day, the six inches would be removed in $6/324$ days = 26.7 minutes. This latter soil could become ponded to six-inch depth, for rainfall rates ordinarily encountered, only if the outlet for the gravel were blocked. In the latter examples the layer of gravel, for definiteness, is taken at four-foot depth, but the answers above are the same if the layer of gravel is at 100 ft depth or any other depth, providing that the layer of gravel drains freely to an exit at atmospheric pressure and that all the soil above the gravel layer is in the one case of one inch per day permeability, and in the other, of 324 inches per day. In the latter cases the thickness of the ponded water in its effect on the hydraulic gradient has been neglected. If this is taken into account, then in the case of the soil of permeability one inch per day the seepage rate when the gravel is four feet deep would be $4.25/4$ inches per day, and when the gravel is 100 ft deep, $100.25/100$ inches, with values 324 times as large for the other soil. It is recognized that uniform soil seldom if ever exists to a depth of 100 ft. Ordinarily there will be layers of varying permeability, and one layer, if it is of appreciable thickness, and of very low permeability compared to the rest of the soil, may for practical purposes completely govern the vertical seepage rate.

Use of the theory to calculate soil permeability--In the last section a formula, $T = ta/\bar{Q}$, was given which expresses the time T for ponded water to fall a distance t. If the time T and the distance t are observed and drain spacing a and all parameters in $\bar{Q}$ are known except the soil permeability, the soil permeability may be calculated. This was done for an area at the Agronomy Farm of Iowa State College where a ponded area developed after a series of heavy June rains. In this area six-inch tile drains were at four-foot depth and 80-foot spacing with a layer of clay at about five feet. The depth of water averaged six inches initially and required 24 hrs for removal. Taking Q from Figure 8 to be about $0.467K$ so that $\bar{Q} = 0.467 \times (1 + 0.25/3.50)\,K = 0.5\,K$ (K in inches per day), the formula $T = ta/\bar{Q}$, becomes $1 = (1/2)(80)/(0.5K)$ yielding $K = 80$ inches per day. This calculation, it is to be remembered, does not take into account the constricting effect at the spaces between the tiles. The value will be higher if this factor is taken into account. Neither does the calculation consider any departures of the soil permeability from a uniform value, particularly any departure which might exist immediately above the drain as discussed previously.

The soil permeability K may also be obtained from (11) or (15) by measuring the outflow rate from drain tubes, together with a knowledge of the other parameters. If the depth to impervious layer h and the drain spacing a are not known, (11b) may be used and the results will be correct (compare Figure 8) to better than about 60 per cent accuracy. Furthermore, in (11b) the drain diameter $2r$ is not at all critical and may be taken equal to six inches ($r = 1/4$ ft). The formula for permeability then becomes, neglecting t and r compared to d, $K = (Q/2\pi d) \log_e 2d/r = 0.159\,(Q/d) \log_e 8d = 0.366\,(Q/d) \log_{10} 8d$ (ft/day, if Q is in ft^3/day per ft of drain tube, and d is in ft).

This result is correct to better than 50 per cent for ordinary cases. In view of the wide range in permeability values encountered in soils (factors of 100 are not uncommon) the result is a remarkable one, but one which could not have been predicted without a thorough study of the way in which the various parameters enter the problem. The last formula cannot, of course, be used if there are surface inlets to the drain into which surface water is running. Also this formula, when used for tile lines, is subject to any necessary modifications resulting from constricting effects on the flow at the tile joints.

It is not intended here to imply that soil permeability should first be measured after drains are installed. On the contrary, soil permeability [KIRKHAM, 1945b] should be measured prior to installation, the theory then being used to give the proper drainage design. After underdrains are installed changes in permeability (as due to cropping practices) may be measured by observing drain outflow.

Summary--A theoretical analysis is given for the problem of flow of water into long horizontal tubular drains in water-saturated soil of uniform permeability covered with ponded water and overlying an impervious layer. The theory applies insofar as the flow is uniformly distributed along the drain tubes, and hence applies to tile drains if they are surrounded by a previous material; otherwise the results, except as they bring out general features, are, in the case of tile drains, subject to any modification necessary to take into account the width of the small inlet space at tile joints.

Formulas are developed for (1) the quantity of water Q entering unit length of drain tube per unit time; (2) the rate of intake Q' of water at the soil surface; (3) the height ϕ to which water will stand at equilibrium in piezometers placed in the region of flow; and (4) the stream function ψ. The parameters in the problem (see Fig. 1) are drain depth d, drain spacing a, depth to an impervious layer h, drain diameter 2r, thickness of ponded water t, and soil permeability K. The equations are noteworthy in that they are general for these many variables.

For each physical quantity of interest two sets of expressions in the form of infinite series are derived. One set is convenient for calculation when the drain spacing is equal to or greater than about two times the depth from the soil surface to the impervious layer, and the other when the drain spacing is about equal to or less than about two times the depth from the soil surface to the impervious layer, either set being suitable for intermediate spacing. For practical problems, and to an accuracy of greater than 98 per cent, only the zero and first order terms are needed. In many cases only the zero order term is needed for about 95 per cent accuracy.

The theoretical results bring out the following points:

(1) The most important single geometrical factor governing rate of seepage of water from soil into drains is the drain depth. Doubling the depth of drains will nearly double the rate of flow. This will not be true if the drains approach an impervious layer.

(2) The flow of water from the soil into drains varies very little with changes in drain diameter. At four-foot depth increasing the drain diameter from three inches to 12 inches, 400 per cent, increases the rate of water inflow to the drains approximately 50 per cent if the drains are running empty and only 20 per cent if the drains are running full.

(3) The surface rate of intake of water immediately over drains is much greater than it is at distances removed from the drains, and the effect is accentuated if the impervious layer is near the bottom of the drains. For six-inch diameter drains with centers 4.5 ft deep and 100 ft apart, the surface inflow rate midway between the drains is, when the impervious layer is at great depth, about 1/50 of that at the soil surface above the drains; and when the impervious layer is 1.25 ft below the bottom of the drains the surface inflow rate midway between drains is only 1/140,000 of that at the surface above the drains. For this reason, especially in soils of low permeability, the contour of the ground above drains should be higher midway between drains than over drains if surface water is to be removed rapidly (see Fig. 5A).

(4) Because of the relatively rapid rate of flow near drains, leaching occurs most rapidly there. Leaching effects are small midway between drains and extremely small midway between drains if there is an impervious layer near the drain bottoms. Leaching midway between drains will be increased if the surface is not maintained in a constantly ponded condition.

(5) The drain inflow rate into a single drain is practically independent of the distance to neighboring drains. This means that drains on 50-foot spacing will remove twice as much ponded water per unit time from a field as will drains on 100-foot spacing, and four times as much as will drains on 200-foot spacing.

(6) The presence of an impervious layer near the drain bottoms cuts down the total inflow rate to the drains. The maximum reduction occurs when the drains lie on the hardpan.

(7) The soil permeability may be calculated by measuring the time for ponded water to fall a certain distance, or by measuring the rate of outflow from the drains. Estimates of soil permability can be made to about 50 per cent accuracy for any common drain sizes, depths, and spacings with the aid of the formula

$$K = 0.366\,(Q/d)\,\log_{10} 8d$$

ft per day, where Q is the drain outflow rate in cubic feet per day per foot length of drain and d is the drain depth in feet. This result is remarkable in that it does not involve drain spacing, depth to an impervious layer, or drain diameter.

(8) If the soil permeability is known, the theory may be used as an aid in a rational design of drainage systems.

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(Manuscript received September 29, 1947; presented by title at the Twenty-Eighth Annual Meeting, Washington, D. C., April 29, 1947; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30 Number 3 June 1949

THE LONG TERM PRECIPITATION - RUNOFF RELATION AS THE BASIS FOR FORECASTING WATER SUPPLY

Merrill Bernard

Abstract--This paper describes the technical and operational aspects of the United States Weather Bureau's water supply forecasting service in the western states. A consistent and unexpectedly high correlation between precipitation as measured at relatively low and intermediate elevation stations operated by the Weather Bureau and seasonal runoff was revealed in 1940. From its precipitation network of 2,500 stations in the West, nearly 350 are serving as reporting stations for computing water-year flow volume forecasts. The significance of the length of record period is discussed as are the statistical procedures for progressively substituting observed for statistical data as the season progresses.

Most problems of the field of applied hydrology are involved in one way or another with the precipitation-runoff relation. Some are associated with the engineering design of water-control structures, others with operations heavily dependent on a fore-knowledge of streamflow, as in the management of irrigated agriculture, the generation of power, the procurement of urban and industrial water supplies, or the operation of navigation controls.

In 1942, the United States Weather Bureau, under its basic authority to "gage and report on the rivers," initiated what has proven to be a successful water-supply forecasting service in the western states. The procedure used in the West has been found to yield equally satisfactory results within the climatology of New England. It is with this demonstration that my paper deals.

Runoff is never coincident with the precipitation causing it. The time offset ranges from that measured in minutes, as in urban storm sewer areas, to weeks and even months where the runoff comes from precipitation which has accumulated as a snow pack as is the case in the high mountainous areas of the West. This fortunate circumstance has been exploited to the advantage of the western water user, and, as will be seen, has made it possible to develop a forecasting technique of unusual range and dependability.

The development referred to has taken place in a region where an economy heavily dependent on water supplies from snow falling in high mountainous areas makes it necessary to have a forecast of available water sufficiently far in advance to become the basis of operational plans such as the determination of irrigated acreage to be cropped, the amount of seed to be purchased, standby fuel to be contracted, and surplus hydro-electric power to be disposed of. In water year 1949 the Weather Bureau will issue water-supply forecasts for about 150 irrigated valleys in the Columbia, Colorado, Rio Grande, Sacramento, Platte, and Great Basins.

The success of the statistical approach to water-supply forecasting from precipitation is attributable to three favorable circumstances: (1) The availability of networks of precipitation stations maintained by the Weather Bureau, and stream-discharge stations operated by the Geological Survey at which records have been kept for a sufficient time, 25 years or longer in most cases, to produce reliable statistical correlations; (2) A high degree of interrelation between precipitation observed at low, intermediate and high elevations; and (3) The forecasting advantage of snow accumulation through the winter months, offsetting, in time, those months in which the water thus stored is utilized.

The statistical significance of length of record is illustrated in Figure 1. The progressive improvement in accuracy and dependability of a regression line as the length of record increases is obvious. Both the slope and position of a regression line developed from a record of limited length are subject to error because the few years used in the limited sample may prove to be poorly representative of events observed over a longer period of time. For example, assume that the regression computed from the observed data is as shown in Fig. 1. If only four years of record were available for the computation, the probability is 93 per cent (corresponding to twice the standard error) that the true regression line is located in the region bounded by the two widely separated curves labeled n = 4. However, the probable position of the regression line as computed from 32

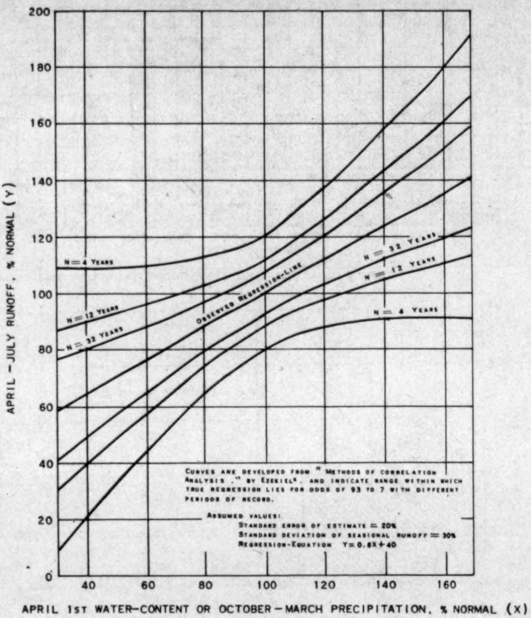

Fig. 1--Statistical significance of length of record

years of observations is limited by the curves labeled n = 32. There is a pronounced improvement in the stability of the regression line, and, therefore, in the accuracy of the relationships expressed, with the progressive increase in the number of observations.

Until recent years the precipitation records of the West were discredited as a basis for forecasting water supply on the grounds that they were not representative of the area contributing the runoff, it being pointed out that the greater number of observing stations were at relatively low or intermediate elevations. Figure 2 shows the elevation distribution of the stations representative of the Weather Bureau's reporting network in the western states. The greater number lie between 2,000 and 8,000 ft above sea level.

Figure 3 is a frequency distribution of correlation indices for the precipitation-runoff relation used in preparing the water-supply forecasts. In nearly 50 per cent of the cases the correlation index is greater than 0.90, and in about 90 per cent the index values are greater than 0.80. It should be borne in mind that the correlation we are here considering is that between precipitation observed at the stations whose related elevations are shown in Figure 2 and runoff, independently measured as stream flow from catchment areas extending into the highest elevations. The conclusion must be reached, therefore, that there is a marked interdependence and, consequently, a high correlation between monthly precipitation depths at relatively low, intermediate, and high elevations in Western mountain areas.

The development of the procedure cannot, within the scope of this paper, be presented in complete detail. Following are the steps involved:

(1) Assembly of precipitation and stream-flow data, by months. (Practically all data necessary are to be found in the published bulletins of the Weather Bureau and the Geological Survey.)

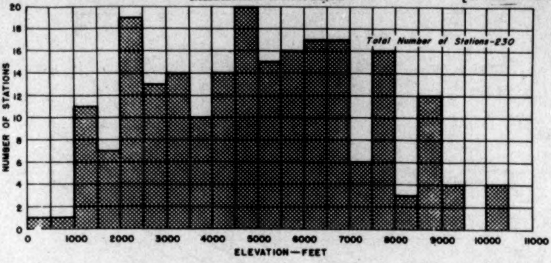

Fig. 2--Frequency distribution of elevation of reporting stations

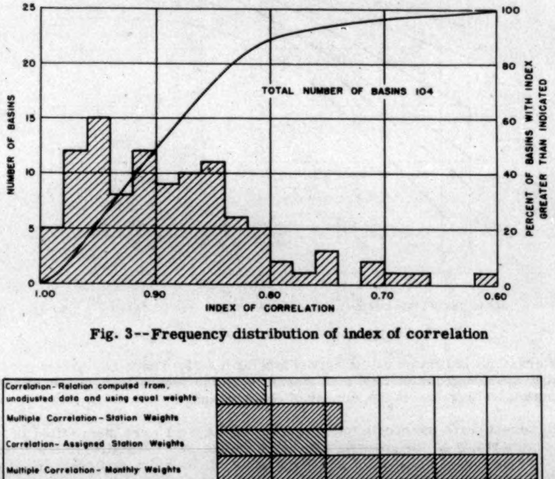

Fig. 3--Frequency distribution of index of correlation

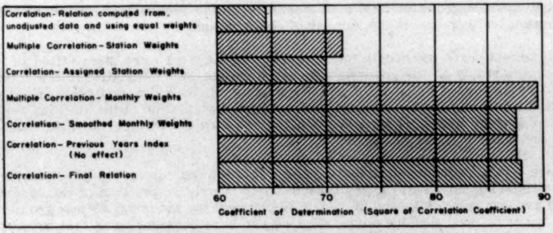

Fig. 4--Progressive improvement of coefficient of determination with successive steps in the analysis, Kennebec River at The Forks

(2) Adjustment of the individual precipitation record to the most recent period of record through comparison with the regional precipitation base.

(3) Preliminary adjustment of runoff to the most recent period of record through comparison with the regional precipitation base.

(4) Determination of precipitation station weights through multiple correlation in which Q is season's runoff, P_n is the season's precipitation at station n, and A_n is a constant

$$Q = a_0 + a_1 P_1 + a_2 P_2 + \dots + a_n P_n \quad \text{(1)}$$

(5) Determination of effective basin precipitation E, by months

$$E = a_1P_1 + a_2P_2 + \dots a_n P_n \quad \dots\dots\dots\dots \quad (2)$$

(6) Determination of relative effect of each calendar month by multiple correlation in which b_n is a constant

$$Q = b_0 + b_1 E_{Oct} + b_2E_{Nov} + \dots + b_nE_{June} \quad \dots\dots\dots\dots \quad (3)$$

(7) Computation of the basin precipitation index I for each year

$$I = b_1 E_{Oct} + b_2E_{Nov} + \dots + b_nE_{June} \quad \dots\dots\dots\dots \quad (4)$$

(8) Determination of relative effect of previous year's precipitation by three-variable correlation in which c_n is a constant

$$Q = c_0 + c_1 I + c_2I_{prev.\ yr} \quad \dots\dots\dots\dots \quad (5)$$

(9) Computation of total precipitation index, X, computed for each year of record

$$X = I + (c_2/c_1)\, I_{prev.\ yr.} \quad \dots\dots\dots\dots \quad (6)$$

(10) Final adjustment of runoff by double-mass plotting of computed vs observed runoff.

(11) Graphical correlation of adjusted runoff with total precipitation index

$$Q = f\,(X) \quad \dots\dots\dots\dots \quad (7)$$

(12) Computation of reliability factors--correlation index, average error, and standard error.

(13) Computation of statistical indices for partial season. Degrees of freedom have been conserved in a practical manner by: (1) Grouping related variables into separate regressions; (2) modifying the computed weights of those stations showing extreme variability which are obviously out of accord in a system so highly intercorrelated; and (3) smoothing monthly weights to a second or third order curve.

So it is seen that the development is not one of adding variables to the correlation, but of a progressive refinement of the basic parameters, precipitation and runoff. Figure 4 shows this progressive refinement in terms of the coefficient of determination (per cent of variance accounted for).

The seasonal precipitation average for all stations, as observed, accounts for only about 65 per cent of the variance in observed runoff on the Kennebec. When the data are adjusted and the precipitation is weighted by stations and months, almost 90 per cent of the variance is accounted for. In this example, the last two refinements contributed no improvement to the correlation; however, the introduction of the previous year's precipitation index and recognition of curvature in the final expression of the relationship materially improve the results in the greater number of cases.

In preparing to render a forecasting service, the needs of the client should have first consideration. If he is generating power, he may at all times have to be prepared to meet conditions fixed by the lower extreme of precipitation, despite the fact that the statistical odds are very slight that such a condition will prevail. A flood-control operation, on the other hand, may be forced to consider the upper extreme of possibility, even though the odds are equally small that precipitation for the remaining months of the season will reach these proportions. Most operational plans, however, can be held within the most likely range between the upper and lower quartiles, giving the operator the benefit of the best possible odds, for gamble he must if he is to pit his wits and judgment against the whims of old Mother Nature. Accordingly, five forecasts are prepared under the assumption that it is possible for the precipitation for the remaining portion of the winter season to be equal to the median, the upper or lower quartiles, or the maximum or minimum of record, the operator choosing that which best expresses the risk he is prepared to take. For instance, the chances are about one to three that the season's flow volume will reach or be greater than the upper quartile forecast, while the odds are about three to one that the lower quartile forecast will be exceeded. Many operations warrant such a conservative gamble if the odds can be made known in advance.

The first Weather Bureau forecast of the season is issued as of January 1. At this time the value of one parameter, the precipitation index of the previous year, which usually contributes about 15 per cent of the total index, is known, as well as indices representing observed precipitation for October, November, and December. It is here the admission must be made that the precipitation for the period January through June is not known, nor can it be, for there is no successful method of forecasting the actual weather more than five days in advance. This is less discouraging than it appears, for on January 1, in most cases, over 50 per cent of the data required to solve the forecasting equation are observed. The five forecasts of known odds are now computed under the assumptions previously mentioned, that precipitation for the remaining portion of the season will be equal to the maximum, the minimum, the upper and lower quartiles, and the median of record.

At the beginning of each of the subsequent months, February, March and April, confirming or modifying forecasts are made by substituting observed data for the statistical. The effect is as shown in Figure 5. It is seen that the median forecast as of April 1, as well as the observed flow volume, maintained positions between the quartiles established as early as December 1. It must be expected, however, that by definition of the quartiles, the observed flow will fall outside of the interquartile range in one half of the years of the ultimate record.

This rather detailed explanation is considered necessary to an understanding of the immediate subject. It was natural that an experience in procedure development which has met with no case of inapplicability throughout the mountain states of the West should invite the question, "What would happen if the forecasting procedure were applied to basins in the Northeastern portion of the country where there is also need for a long-range forecast of runoff for utilities operations?" Accordingly, a test was made on three basins, the Kennebec River at The Forks, Me.; the Pemigewasset River at Plymouth, N. H.; and the Quinebaug River at Jewett City, Conn. Their locations are shown in Figure 6. An added purpose of the study was to move southward sufficiently far to include a basin in which no extensive accumulation of snow occurs during the winter months, in which case the time lag, as a forecasting advantage, would be reduced to a minimum.

A climatological comparison of the three eastern basins with that of the Spokane River above Spokane, Washington, discloses a somewhat different distribution throughout the months of greatest precipitation; nevertheless, the forecasting procedure for all four basins, and the techniques followed in their development, are identical.

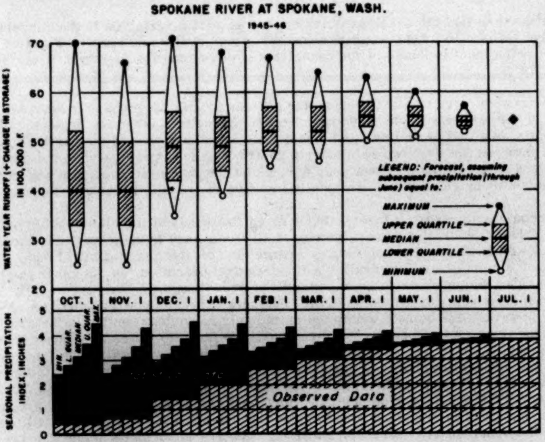

Fig. 5--Data on forecasts, Spokane River at Spokane, Washington, 1945-1946

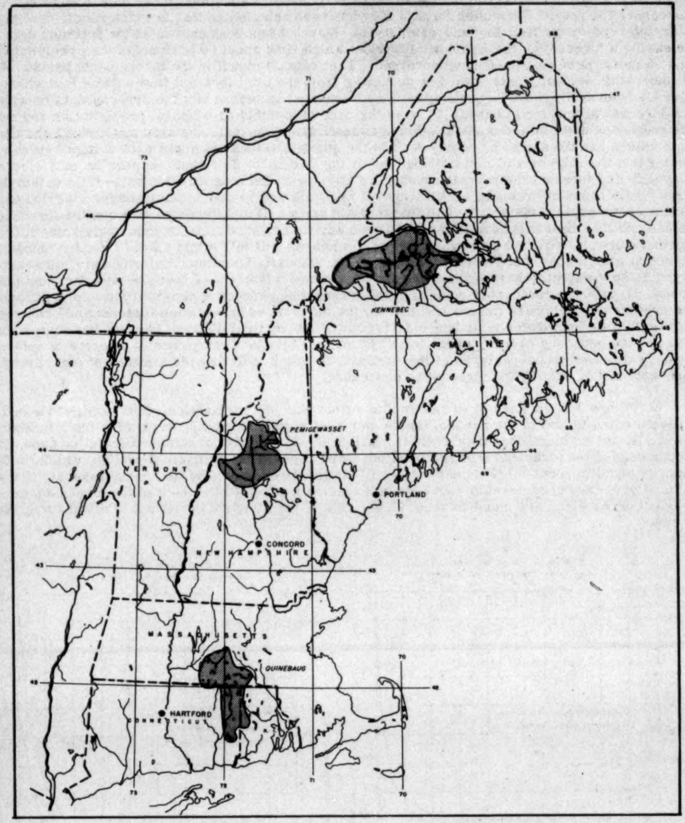
KENNEBEC
MAINE
PEMIGEWASSET
VERMONT
PORTLAND
CONCORD
NEW HAMPSHIRE
MASSACHUSETTS
QUINEBAUG
HARTFORD
CONNECTICUT
71
70
69
68
72
73
47
46
45
44
43
42

Fig. 6--Map of New England showing locations of watersheds studied

Mention has been made of the favorable circumstance in the West under which a long-range water supply forecast can be formulated, that of an extended period between the time precipitation falls and the time it is released as runoff. On the Spokane, by January 1, when the key forecast is released, about 55 per cent of the data utilized in the forecast are observed, while only 17 per cent of the runoff has occurred. On the Quinebaug, by the time 55 per cent of the data are available, nearly 40 per cent of the runoff has taken place.

How, now, can the skill of the forecaster, in terms of the accuracy and dependability of a forecasting procedure be appraised? Obviously, the favorable opinion of the operator being served is the best gage, but at the moment interest is directed at a somewhat more objective measure of success. The period December through May has been selected as that in which runoff is of particular interest to the New England water user. March 1 has been chosen as the optimum date for releasing a forecast on the Kennebec River, at which time about 60 per cent of the precipitation, and 20 per cent of the runoff have occurred. The residual runoff in the three-month period, March through May, is easily determined by deducting from the total forecast flow volume that which has already been delivered. To begin with, the forecaster has before him the array of data on which the forecast procedure is based. If, as in the case of monthly or seasonal precipitation and runoff, the frequency distribution is reasonably symmetrical, or normal, the arithmetic mean and the median values are the same, or nearly so, and the quartile values are about equi-distant between the center and the extremes of the distribution. If the forecaster is a cautious soul, he may elect to play safe and forecast the normal runoff year after year, knowing that this value falls within the most likely range of probable verification. If he is allowed to stay in business for a period equal to that of the present record, he will find that his errors (the differences between the forecast values and the observed) have fallen about as many times above as below his single value forecast. Furthermore, he will find that two-thirds of his misses will fall within a band fixed by boundaries placed at a distance from the normal equal to the standard deviation. Unfortunately, this range of error is so great as to have neutralized the operational advantage of the forecasts for most purposes. If, now, the forecaster resorts to the forecasting procedure provided him, he will find that the greater percentage of the errors, that is, the differences between the forecast and observed values, will be less than one standard deviation. If the vertical distance between the regression line and the boundary of this "error band" is marked by a percentage scale, a series of internal bands, expressed as percentages of the standard deviation, will provide a means of classifying the forecasts and of judging the forecasting procedure.

Figure 7 is an attempt to clarify this rather obscure explanation. It is seen, at the end of a period equal to that of the record, that 50 per cent of the forecasting errors for the Kennebec (Curve B) are so small that they would fall within the 30 per cent of standard deviation band, while 70 per cent of the forecasts will verify within 50 per cent of the standard deviation, which, in this case, is equal to about 1 1/2 inches of runoff. However, the single value normal forecast (Curve A) is to be penalized considerably. As is to be expected in about 70 per cent of the forecasts, errors have occurred which are equal to about 90 per cent of the standard deviation, or about three inches of runoff.

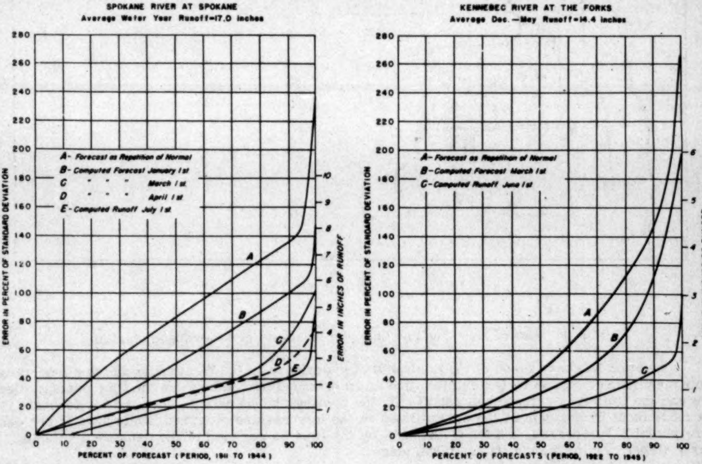

Fig. 7--Forecasting effectiveness of the precipitation-runoff relation

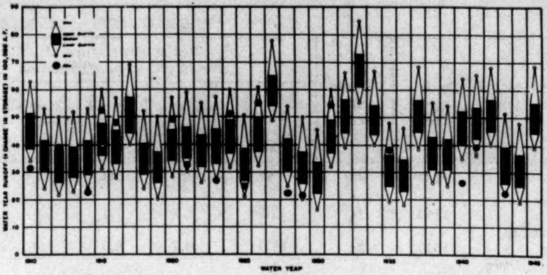

Fig. 8--January 1 forecasts, Spokane River at Spokane, Washington

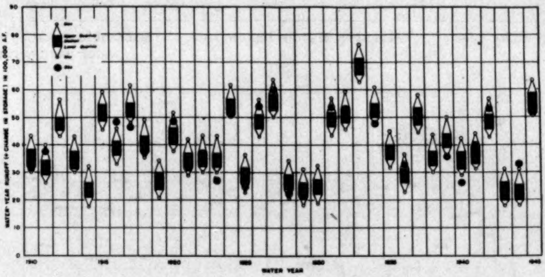

Fig. 9--April 1 forecasts, Spokane River at Spokane, Washington

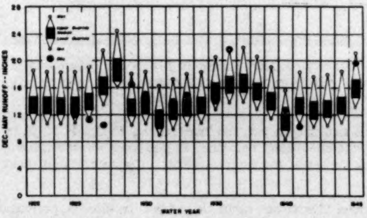

Fig. 10--March 1 forecasts, Kennebec River at The Forks

In appraising the accuracy of the precipitation-runoff relation, as expressed by the forecasting equation, the verification is still further improved (Curve C). In this case, 50 per cent of the computed runoff values will be in error to an extent less than 17 per cent of the standard deviation, while 70 per cent will have error of less than 28 per cent. There will, of course, be a few bad busts, which should be accepted philosophically by both the forecaster and the operator he is serving. On the Kennebec, one out of ten single value normal forecasts (Curve A) will miss by amounts equal to 150 per cent of the standard deviation, while the forecaster utilizing the forecasting procedure must expect one out of ten to miss by 110 per cent of the standard deviation (Curve B). We see that only one out of ten of the computed runoffs (Curve C) will be in error by more than 45 per cent of the standard deviation, which, reduced to runoff depth, is a little less than 1 1/2 inches.

Table 1--Reliability factors of precipitation-runoff

Basin	Drain-age area	Years of record	Reliability factors of precipitation-runoff relation				
			Dec.-May 25-yr normal runoff	Aver-age error	Aver-age error	Stand-ard error	Index of corre-lation
	sq mi	in	in	in	pct	in	
Spokane River at Spokane	4350	34	17.0[a]	1.2	7.1	1.6	0.97
Kennebec River at The Forks	1570	24	14.4	0.7	5.0	1.0	0.94
Pemigewasset River at Plymouth	622	36	20.5	1.0	5.0	1.4	0.95
Quinebaug River at Jewett City	711	27	15.6	1.3	8.3	1.8	0.85

[a] Period is water year. [b] Period is March-September. [c] Ratio of March-September and water year normals

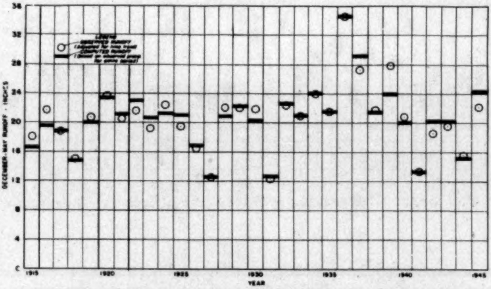

Fig. 11--Pemigewasset River at Plymouth, comparison between observed runoff and computed runoff using precipitation-runoff relation

Reliability factors are shown for the four basins in Table 1. It is seen that the high correlation index of the precipitation-runoff relation is reduced when utilized for forecasting, because of the fact that data for that part of the season yet to be experienced must be assumed to conform to a selected statistic.

Figures 8, 9, 10, and 11 will not meet the whole-hearted approval of the statistician. He will object to a demonstration which utilizes the same data used in developing the procedure. It has been found however, in the development of the water-supply forecasting procedures described herein, that it is altogether unprofitable to exclude a set of test years from the record, which we believe can serve a better purpose in contributing to the stability of the correlation. Furthermore, successful verifications throughout the past three or four years of actual experience support this position.

Within the range of available records it can be said that the weather pattern of the past can be taken as that to be expected in the future. Another way of saying this is that we have accepted the period of the available record (20 to 35 years) as a representative sample of that which will accumulate through the years ahead. On this basis, Figure 8 can be accepted as a preview of a future forecasting experience on the Spokane River. The five selected probability forecasts as of January 1 are compared with the observed flow volumes for the water years of record.

relation and verification of March 1 forecasts

March 1 forecasts									Ratio of March-May and Dec.-May normals
Period, Dec.-May				Period, March-May					
Average error	Average error	Standard error	Index of correlation	Normal runoff	Average error	Average error	Standard error	Index of correlation	
in	pct	in		in	in	pct	in		
1.9[a]	11.4	2.4	0.90	12.3[b]	1.9	15.9	2.4	0.78	0.71[c]
1.7	11.8	2.4	0.60	11.7	1.7	14.5	2.4	0.54	0.81
2.4	11.7	3.4	0.58	15.8	2.4	15.4	3.4	0.49	0.79
2.5	16.1	3.0	0.61	9.7	2.5	25.8	3.0	0	0.62

Figure 9 gives the same picture, but the forecasts are as of April 1. It is noted that the extreme and quartile forecasts have converged on the single value median forecast to the point that the errors inherent in the procedure are of more significance than the small remaining percentage of statistical data utilized.

In the same manner, Figure 10 compares the March 1 forecasts for the Kennebec River with the observed flow volumes for the period December through May.

Figure 11 compares the observed flow with that computed as of June 1 on the Pemigewasset. The conformity of the computed and observed patterns for the Quinebaug would be somewhat less complete because of a lower correlation index and a higher standard error.

A survey of service demand will be needed to determine the extent to which water-supply forecasts of this kind will be of value to the New England operator. It is apparent that the potentialities exist on all basins in Vermont, New Hampshire, and Maine. The further utilization of the seasonal flow forecast as a base upon which to superimpose the shorter range flood-forecast should receive particular attention.

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(Manuscript received June 14, 1948; presented at the New England Meeting, Cambridge, Mass., Sept. 18, 1947; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

A COMPARISON OF THE SEDIMENT LOADS CARRIED BY THE MISSOURI AND UPPER MISSISSIPPI RIVERS

Gunnar M. Brune

Abstract--A comparative study was made of the sediment load carried by the Missouri and Upper Mississippi Rivers, making corrections for the types of sampler used, abnormal runoff, and bed sediment. At the confluence of these two rivers, long-term sediment concentration in the Mississippi was found to be 20 per cent of that in the Missouri. However, the mean annual rate of sediment production per square mile of drainage area for the Mississippi at the confluence was found to be 84 per cent of that of the Missouri. The reason that the rate of sediment production of the Mississippi is 4.2 times as great, relatively, as its sediment concentration, in comparison with the Missouri, is that the annual runoff per square mile in the Upper Mississippi basin averages 4.2 times that in the Missouri basin. Contrary to the usual condition, the sediment concentration and rate of sediment production for both these rivers increases with increasing size of drainage area up to about 200,000 sq mi.

Introduction--It is almost impossible to view the confluence of the Mississippi and Missouri Rivers from the air without noticing the difference in turbidity of the "Big Muddy" and the Mississippi as the waters mix. Turbidity is a reflection primarily of concentration of fine sediment particles suspended in the stream flow. Available records show that the average suspended sediment concentration in the Missouri is several times that of the Mississippi at their confluence. This raises a pertinent question. Does the greater sediment concentration in the Missouri result from a higher average rate of erosion throughout the Missouri River basin? A study of existing data was made in an effort to answer this question and the related problem of the distribution of sources of sediment within each of these major drainage basins.

Method of study--For the purposes of this study, 20 suspended sediment records were used, 12 on the Missouri and eight on the Upper Mississippi River (see Fig. 1). The Missouri River records were all collected by the Corps of Engineers, Department of the Army, from 1929 to 1932 [UNITED STATES WAR DEPARTMENT, 1935] and from 1939 to 1945 (unpublished data). The Mississippi River records were collected from 1932 to 1933 by the St. Paul District, Corps of Engineers [UNITED STATES ENGINEER OFFICE, 1935], and from 1942 to 1947 by the Rock Island District, Corps of Engineers (unpublished data). The records were all based on systematic suspended sediment sampling, except that at Keokuk, Iowa, the sediment trapped in the navigation pool was also measured. Table 1 gives the period of record for the sampling stations.

Because systematic sediment sampling on these two rivers has not been done at the same time or with the same type of sampler, a detailed comparison of the sediment loads involves several adjustments of the data.

Research studies made cooperatively by several Federal agencies at the Iowa Institute of Hydraulic Research resulted in the scientifically designed D-43 depth-integrating suspended-sediment sampler. This sampler has now been widely adopted and is considered here as a standard of accuracy. Comparative field tests of the D-43 and other types of samplers made by personnel of the using agencies have given a basis for adjusting older records to the standards to be expected with the D-43 sampler.

The Omaha sampler used in collecting the Missouri River sediment samples was found by comparative field tests to collect an average of 18 per cent more sediment than the D-43 sampler [UNITED STATES GOVERNMENT, 1944]. The St. Paul sampler was found to collect approximately the same amount of sediment as the D-43. The various types of Rock Island samplers were found to collect 13 to 39 per cent more sediment than the D-43. The sediment records used in this study were, therefore, corrected to D-43 standards in order to place them on a comparable basis.

Because the sampling was done during different periods it was necessary to correct all of the sediment records for abnormal runoff. During the period when the earlier Missouri River sampling was done, 1929-1932, the river discharge was for the most part below normal. When the four upper

Table 1--Actual measured quantities of suspended sediment at the various stations

Station	Period of record	Length of record	Drainage area	Average annual measured suspended load
		yr	sq mi	million tons
Ft. Benton, Mont.	1929-1932	3.00	24,570	0.6
Wabasha, Minn.	1932-1933	1.00	56,610	0.2
Winona, Minn.	1932-1933	1.00	59,245	1.1
LaCrosse, Wis.	1932-1933	1.00	62.780	1.6
Clayton, Iowa	1932-1933	1.00	79,200	3.3
Dubuque, Iowa	1942-1946	3.88	82.200	9.0
Burlington, Iowa	1942-1946	3.87	115,000	18.5
Keokuk, Iowa	1913-1936, 1943-1946	26	119,000	27.3[a]
Hannibal, Mo.	1943-1945, 1946	1.98	137,000	41.6
Williston, N. D.	1929-1932	3.00	164,455	37.7
Mobridge, S. D.	1929-1932, 1939-1945	10.00	208,710	64.6
Sioux City, Iowa	1929-1932	3.00	314,617	75.2
Omaha, Nebr.	1929-1932	3.00	322,820	88.9
Plattsmouth, Nebr.	1929-1932	3.00	413,730	105.0
Leavenworth, Kans.	1929-1932	3.00	425,010	121.8
Kansas City, Mo.	1929-1932	3.00	489,162	156.6
Boonville, Mo.	1929-1932	3.00	505,710	145.0
Howard Bend, Mo.	1929-1932	3.00	529,125	151.1

[a] Including sediment trapped in Keokuk Reservoir.

stations on the Mississippi River were sampled, 1932-1933, the discharge was considerably below normal. When the four lower stations on the Upper Mississippi were sampled, 1942-1947, on the other hand, the river discharge was above normal.

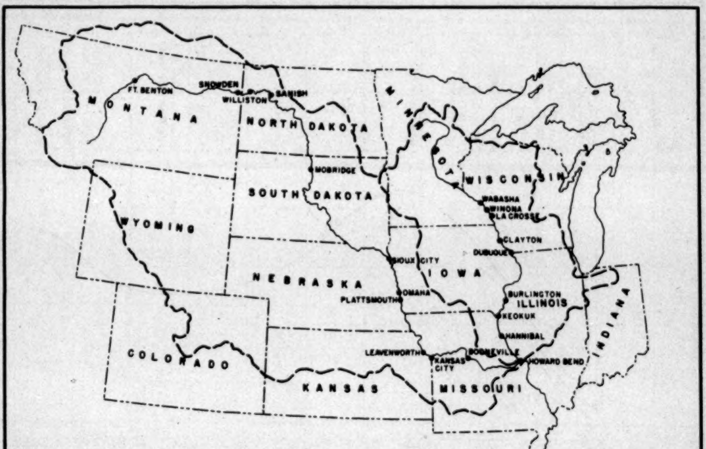
MONTANA
FT. BENTON
SNOWDEN
WILLISTON
SANISH
NORTH DAKOTA
MINNESOTA
MOBRIDGE
SOUTH DAKOTA
WISCONSIN
WABASHA
WINONA
LA CROSSE
CLAYTON
DUBUQUE
WYOMING
SIOUX CITY
IOWA
NEBRASKA
OMAHA
PLATTSMOUTH
BURLINGTON
ILLINOIS
KEOKUK
HANNIBAL
INDIANA
COLORADO
LEAVENWORTH
KANSAS CITY
BOONEVILLE
HOWARD BEND
KANSAS
MISSOURI

Fig. 1--Map showing location of sampling stations

In order to determine what rate of sediment production may be expected over a long-term period, each record was adjusted to a mean runoff for that station. It was assumed that the annual rate of sediment production varies roughly as the square of the annual runoff or according to the empirical equation $S = CR^{2.0}$, in which S is the annual sediment load, C is a coefficient and R is the annual runoff. It is recognized that this exponent may vary considerably for different stations, but the power of 2.0 is probably close to the average for this region. Straub, in his Missouri River studies [UNITED STATES WAR DEPARTMENT, 1935] found that the equation $S = 30.4 \times 10^{-11} Q^{2.16}$ described the curve for average conditions at Kansas City, CAMPBELL and BAUDER [1940] found that the equation $S = 9.5 \times 10^{-9} Q^{2.036}$ described most of the curve for the Red River at Dennison, Texas. BROWN [1945] found comparable relationships in the Southwest and drew curves of the form $S = CR^x$ for the Colorado River at Grand Canyon and Lees Ferry, Arizona, and at Cisco, Utah, for the Green River at Green River, Utah, and for the San Juan River at Bluff, Utah. The exponent in the equation of these curves varies from 1.17 to 2.50, averaging 1.81.

A correction was also made to the suspended load records for bed load carried by these rivers. Straub [UNITED STATES WAR DEPARTMENT, 1935] and others have estimated that the bed load of both these rivers averages ten per cent of the total sediment load. This percentage addition was used in correcting the sediment records.

Studies on the Missouri River during the period 1939 to 1945 by the Corps of Engineers were made in a slightly different way. Sediment load was plotted against monthly discharge for each month of record. Then, by means of flow duration curves and discharge records collected by the Corps of Engineers as far back as 1898, the long-term sediment production indices and concentrations were computed. Where this type of study was available, the earlier records of 1929 to 1932 were not used.

After the data had been brought to a comparable basis by adjusting for types of sampler used, abnormal runoff, and bed sediment, they were plotted in Figures 2 and 3. In Figure 2, long-term sediment concentration in runoff is plotted against size of drainage area. In Figure 3, long-term annual sediment production, in tons per square mile, is plotted against size of drainage area.

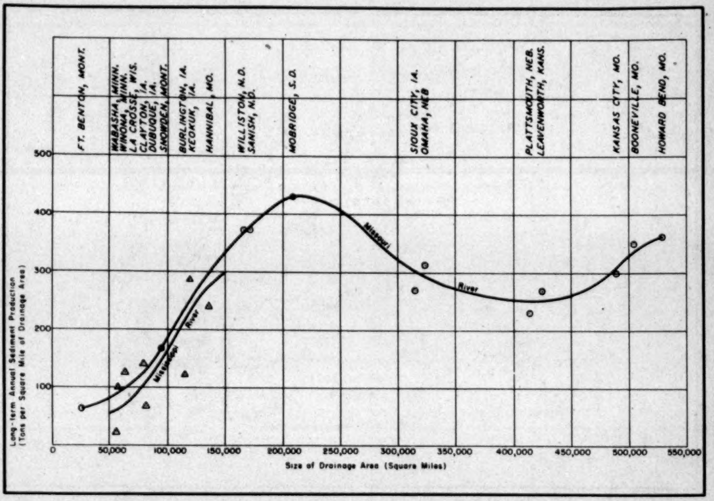

Fig. 2--Comparison of sediment concentration, Missouri and Upper Mississippi Rivers

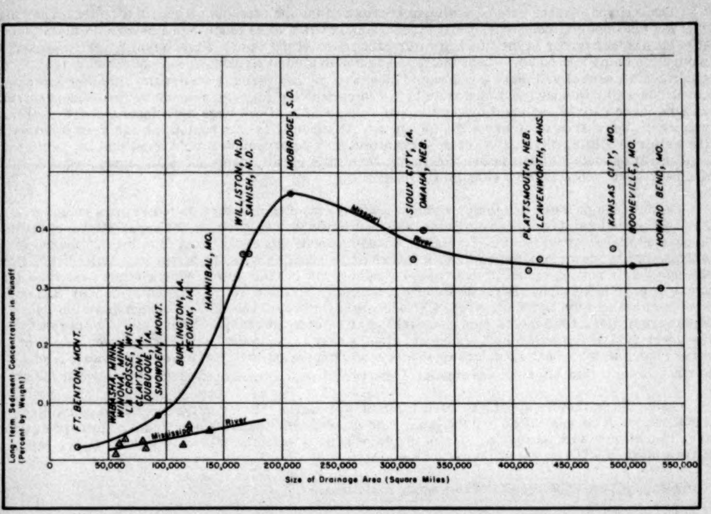

Fig. 3--Comparison of rates of sediment production, Missouri and Upper Mississippi Rivers

Discussion--Figure 2 shows that the Missouri and Upper Mississippi Rivers in their headwaters have approximately the same long-term mean sediment concentration in runoff, 0.02 per cent. This mean concentration rises going downstream on both rivers, until at their confluence near St. Louis the concentration in the Mississippi is about 0.07 per cent and in the Missouri about 0.35 per cent. Although the sediment concentration increases in both rivers with increasing size of drainage area, the concentration increases much more slowly in the Mississippi than in the Missouri, with the result that at their confluence, the Mississippi has only one-fifth the long-term mean sediment concentration of the Missouri. This, of course, explains the prevailing difference in turbidity of the two rivers at this point.

Figure 3 shows that in their headwaters these two rivers also have approximately the same long-term mean annual rate of sediment production, 65 tons/sq mi of drainage area. Proceeding downstream, the rate of sediment production increases in both cases, to about 300 tons/sq mi for the Mississippi and to 360 tons/sq mi for the Missouri, at the point where the two meet. In this case also, the rate of sediment production increases less in the Mississippi than in the Missouri, but not much less. At their confluence, the Mississippi has a long-term mean annual rate of sediment production, in tons/sq mi of drainage area, 84 per cent as great as that of the Missouri River.

These figures appear to be significant. Why does the sediment concentration in the Mississippi decrease from the equal of the Missouri in their headwaters to only 20 per cent at their junction? Why, on the other hand, does the rate of sediment production of the Mississippi decrease from the equal of the Missouri to 84 per cent of the Missouri rate at the confluence of the two rivers, a figure 4.2 times as great as that for sediment concentration?

The answer is to be found partially in the differing amounts of rainfall and runoff in the two basins. In their headwaters, both rivers have approximately the same mean annual runoff, 250 ac ft/sq mi of drainage area. At their confluence, however, the mean annual runoff of the Missouri is 93 ac ft/sq mi and that of the Mississippi is 390 ac ft/sq mi, 4.2 times as much. Thus, although the long-term sediment concentration of the Mississippi is only about one-fifth that of the Missouri at their confluence, still, because there is an average of 4.2 times as much runoff per square mile in the Upper Mississippi basin as in the Missouri basin, the total sediment load per square mile of drainage area for the two rivers at their junction is almost the same.

One reason that the rate of sediment production for the Missouri River is slightly higher than that for the Upper Mississippi is that streambank erosion is so much more severe on the Missouri River. Another factor is the much greater proportion of the Upper Mississippi River improved by navigation dams and pools. These pools, as demonstrated at Keokuk, Iowa, undoubtedly trap a considerable amount of sediment which would otherwise be delivered downstream. Another interesting result shown by this analysis is that on both rivers both the long-term mean sediment concentration and the mean rate of sediment production per square mile of drainage area increase with increasing size of drainage area up to about 200,000 sq mi. Ordinarily in this region, as has been point out by the writer [BRUNE, 1948], the opposite condition may be expected to hold true, that is, sediment concentration and sediment production per square mile usually decrease with increasing size of drainage area, other factors remaining constant.

In the case of these two major rivers, however, the other factors do not remain constant. Average annual rainfall increases from less than ten inches in parts of the upper Missouri basin to over 40 inches at its mouth. Similarly, annual rainfall increases from less than 25 inches in the Mississippi headwaters to more than 40 inches at its junction with the Missouri. Both rivers flow through gently rolling plains in their upper reaches, but in their lower reaches they pass through areas of hilly topography characterized by much more erodible soils, such as the Loess Hills of western Iowa and the Driftless Area of Wisconsin, Minnesota, and Iowa. Furthermore, in the Mississippi River headwaters numerous lakes act as sediment traps. These are not present in the lower part of the watershed. Land use also is very important. In their headwaters, both of these rivers flow through large areas of forest and grassland, with very little cultivated land. Farther downstream, however, the amount of land in cultivation rises to 80 per cent or more as in Iowa.

All of these factors appear to work together to reverse the normal trend and to cause the mean sediment concentration and the mean rate of sediment production per square mile of drainage area to increase with increasing size of drainage area of both the Missouri and the Upper Mississippi Rivers up to 200,000 sq mi drainage area.

Conclusions--The results of this study show that:

(1) The long-term mean sediment concentration in runoff for the two rivers is approximately the same in their headwaters. Sediment concentration increases downstream in both cases, but much more rapidly in the Missouri, so that at their confluence it is only 20 per cent as great in the Mississippi as in the Missouri.

(2) The mean annual rate of sediment production per square mile of drainage area is also approximately the same in the headwaters of the two rivers. It increases downstream in both cases, but slightly more in the Missouri, so that at their confluence the Mississippi has only 84 per cent as high a rate of sediment production as the Missouri.

(3) The reason that the Missouri has five times as great a sediment concentration as the Mississippi at their confluence but only a 16 per cent higher rate of sediment production per square mile of drainage area, is that the annual runoff per square mile in the Upper Mississippi basin averages 4.2 times that in the Missouri basin.

(4) Contrary to the general condition, the mean sediment concentration and the mean rate of sediment production increase in both these rivers with increasing size of drainage area up to about 200,000 sq mi. This is caused by marked changes in many factors, including rainfall, land use, soils, and topography from headwaters to confluence.

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(Communicated manuscript received June 1, 1948;
open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

MOVEMENT OF WATER WITHIN THE SOIL AND SURFACE RUNOFF WITH REFERENCE TO LAND USE AND SOIL PROPERTIES

Leonard Schiff and F. R. Dreibelbis

Abstract--The major objective of this paper is the development of information on the effect of soil moisture, soil properties, and land use on water movements within the soil and relationships that exist between such water movements and surface runoff. This paper supplements the one presented in 1947 [SCHIFF and DREIBELBIS, 1949]. Use is made of the method, developed in the original paper, for determining rates of water movement within the soil profile on natural watersheds. Data for 1947 are analyzed and interpreted for three watersheds whose soils and covers cause considerable differences in hydrologic performance.

Infiltration rates as high as eight inches per hour occurred. Percolation rates at the bottom of the topsoil ranged from 0.60 to 0.15 in/hr for Muskingum silt loam and from 0.46 to 0.04in/hr for Keene silt loam. Transmission rates or velocities, expressed in linear inches per hour, were obtained for the topsoil and subsoil respectively, as follows: Cultivated Muskingum silt loam 20 and 1.5; cultivated Keene silt loam 20 and 0.83; and forested Muskingum loam 37.5 and 7.5. Initial transmission rates required to absorb various infiltration rates at different soil moisture contents, are presented. It is shown that runoff occurred when the rate of rainfall required a transmission rate greater than could exist in the soil at a given soil moisture. Little runoff occurred when the storage space available within the topsoil exceeded the total ground rainfall. Rates of infiltration decreased and approached a constant rate as the topsoil approached saturation. After saturation of the topsoil the low transmission rates in the subsoil became the controlling factor.

The first paper on this subject dealt largely with the accretion of soil moisture until runoff occurred. This second paper includes information on the time required for soil moisture depletion for the different soil types presented. It is shown that in the interval existing between any two large storms, sufficient storage space developed in the topsoil and subsoil to prevent runoff. However, since low transmission rates in the subsoil prevented full use of this storage space in the subsoil, runoff occurred.

Introduction--The major objective of this paper is the development of information on the effect of soil moisture, soil properties, and land use on water movements within the soil and relationships that exist between such water movements and surface runoff. This paper supplements the one presented in 1947 [SCHIFF and DREIBELBIS, 1949] and considers two major phases of the hydrologic cycle, increases and decreases in soil moisture in relation to surface runoff. The first deals with conditions leading to runoff. The second deals with conditions leading to the development of storage space within the soil. Consideration is also given to rates of water movement within the soil and their influence on the use of pore space to store water. Data, primarily for 1947, are analyzed and interpreted for three small watersheds whose soils and vegetal covers produce considerable differences in hydrologic performance.

Information contained herein may have wide general application due to the considerable difference in permeability of the two soil profiles studied. One soil is classified as well drained while the other is classified as slowly permeable. More specifically Muskingum silt loam is found throughout the North Appalachian Region.

Experimental procedure--The three small watersheds selected for this study are described in Table 1. Data were also studied for Watersheds 109, 123, and 103 for June 16, 1946. On this date watersheds 109 and 123 were in wheat, about 36 inches high. Watershed 103 was in corn, about 11 inches high. Watershed 103 has an area of 0.65 acres; an average land slope of 11.3 per cent; Keene silt loam soil type; and slowly permeable drainage. The watersheds are in a four-year rotation of corn, wheat, meadow, and meadow. For any one of these watersheds the soil type, the crop, and the land use are uniform.

Soil moisture was determined periodically, and frequently before and after storms, with gypsum blocks and by field sampling (gravimetric method). Continuous soil moisture records were obtained with recording tensiometers. Detailed information on soil moisture was obtained in the 0-1, 1-3, 3-5, and 5-7 inch depths representing the top soil and the 7-10 and 10-14 inch depths representing the upper subsoil. Evapotranspiration was determined from changes in soil moisture and from data obtained from the weighing lysimeters. Rainfall was measured by recording rain gages. Runoff measured in precalibrated flumes, was primarily surface flow. Detailed information on methods of making measurements was previously presented [SCHIFF and DREIBELBIS, 1949]. Whenever soil-moisture measurements were not made immediately before storms, daily measurements of percolation and evapotranspiration taken on the nearby lysimeters were helpful in evaluating soil-moisture changes between the time of actual moisture measurements and the time of storm periods.

Terms used are listed below.

Infiltration--The passage of water through the surface of the soil mass, that is, a depth of water over a given area passing through the surface of the soil in a specific period of time.

Percolation--The water passing a given level within the soil mass, that is, a depth of water over a given area passing a specific soil level in a specific period of time.

Transmission--The movement of water downward through a given depth within the soil mass, that is, a linear velocity of water through a given depth of soil.

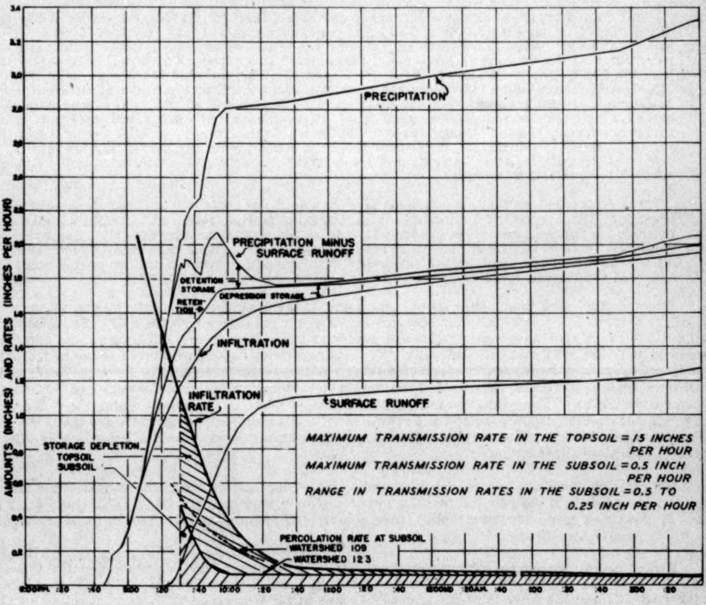

Fig. 1--Analysis of storm of June 16-17, 1946 for Watershed 123

Infiltration and percolation rates, expressed in inches per hour, may be compared directly as they reflect inches depth of water passing given soil levels per hour. Transmission rates, although expressed in inches per hour also, cannot be compared directly with infiltration or percolation rates. They reflect inches depth of soil through which water moves per hour, that is, a linear velocity of water through soil.

Table 1--Description of watersheds selected for study, 1947

Watershed No.	Area	Average land slope	Soil type	Drainage	Land use	Crop and operation
	ac	pct				
109	1.69	12.7	Muskingum silt loam (shale origin)	Well drained	First year meadow, improved	Cultural practices, 6/21 and 6/23 cut hay; 6/23 and 6/24 removed hay; 8/5 cut hay; 8/6 and 8/7 removed hay. Height of vegetation, 3/19, 1 inch; 4/23, 3 inches; 5/23, 8 inches; 6/9, 14 inches; 7/17, 5 inches; 8/8, 3 inches; 9/16, 6 inches; 10/20, 7 inches; 11/13, 6 inches.
123	1.37	5.8	Keene silt loam	Slowly permeable	First year meadow, improved	Same as Watershed 109
113	1.45	9.3	Coshocton silt loam	Fairly drained	Corn improved	Cultural practices, 1/11, 13, 14, 16, 18, 22, 25 manured; 5/12 plowed; 5/27 disked; 5/28 disked, harrowed, planted corn; 6/16, 6/23, and 7/1 cultivated; 10/13 picked corn; 10/15 disked and sowed to wheat. Height crop, 3/19 and 4/29, grass 3 inches; 6/9, corn 2 inches; 7/17, corn 15 to 20 inches; 8/8, corn to 48 inches; 9/16 corn to 50 inches; 11/13, wheat 4 inches.

Results and interpretation--Basic data upon which most of this paper was based have been graphed. Methods of graphing data were previously presented. The concept and methods of analyses were described in detail in the earlier paper, where the storm of June 16, 1946 was analysed for Watershed 123.

Figure 1 graphically illustrates some of the results obtained from this storm. Table 2 presents a summary of data and results of analyses for watersheds 109, 123, and 113 for 15 storms during 1947, and the storm of June 16, 1946, which was included because of its magnitude, for watersheds 109, 123, and 103.

Information contained in Table 2 is discussed below.

(1) A large volume of storage space is available in the topsoil and subsoil, and lower depths, prior to many storms. Transmission rates in the topsoil, maximum being in the vicinity of 20 in/hr for cultivated crops and 40 in/hr for forest, permit the use of storage space in the 0-7 inch depth. If rainfall does not exceed the amount in inches represented by this storage space runoff will occur only under very high intensities. The high intensities required to produce runoff under such conditions occur only rarely. Amounts and rates of runoff that may occur under such circumstances are generally low. This statement does not apply when sealing occurs, primarily on corn watersheds in the early summer. Transmission rates in the subsoil are low, maximum being in the vicinity of 1.50 in/hr for Muskingum silt loam and 0.83 in/hr for Keene silt loam. Little use is made of the storage space available in the subsoil. For each storm in 1947 on each watershed the available storage space in the topsoil and subsoil, 0-14 inches of soil, exceeded the ground rainfall, yet runoff occurred several times. Apparently, complete use was not made of the storage space in the subsoil. In other words, transmission rates in the subsoil limited the use of the storage space available in the subsoil. Table 3 presents the storage available and ground rainfall for storms producing significant runoff, summarized from Table 2. After saturation of the topsoil, rainfall rates in excess of the low infiltration rates, established by the transmission rates in the subsoil, become available for surface runoff. Agricultural practices seem to have contributed to the high rates of transmission in the topsoil of even the Keene silt loam. Erosion of the topsoil is not only the loss of a medium for successful crops but also loss of a usable storage reservoir. Whenever desirable, conservation practices might strive toward increasing the transmission rates below the topsoil. This presupposes reasonable protection of the soil surface against sealing, whereever that is an important factor.

Table 2--Analyses of storms for meadow Watersheds 109

Water-shed No.	Date	Storage available			Ground rainfall	Runoff		Water reached subsoil
		Topsoil 0-7 inches	Subsoil 7-14 inches	Total 0-14 inches		Began	Total	
1	2	3	4	5	6	7	8	9
		in	in	in	in	h m	in	h m
109[a]	June 16, 1946	2.08	1.70	3.78	3.40	21 20	0.47	21 25
123[a]	June 16, 1946	1.55	1.18	2.73	3.61	21 20	1.48	21 31
103[a]	June 16, 1946	1.35	1.11	2.46	3.65	21 17	1.77	21 26
109	Jan. 2-3, 1947	1.08	0.77	1.85	0.94	17 41	0.007	- - - -
123	Jan. 2-3, 1947	0.91	0.56	1.47	0.95	15 28	0.06	- - - -
113	Jan. 2-3, 1947	0.93	0.56	1.49	0.97	- - - -	0	- - - -
109	Jan. 19-20, 1947	0.92	0.56	1.48	1.20	06 20	0.002	- - - -
123	Jan. 19-20, 1947	0.76	0.56	1.32	1.20	03 54	0.36	- - - -
113	Jan. 19-20, 1947	0.84	0.56	1.40	1.23	05 34	0.004	- - - -
109	Jan. 30 1947	0.98	0.66	1.64	1.12	08 34	0.003	- - - -
123	Jan. 30 1947	0.70	0.51	1.21	1.18	11 16	0.38	13 48
113	Jan. 30 1947	0.70	0.43	1.13	1.11	12 20	0.03	- - - -
109	Apr. 15-16, 1947	1.56	1.36	2.92	0.80	- - - -	0	- - - -
123	Apr. 15-16, 1947	1.24	0.63	1.87	0.88	- - - -	0	- - - -
113	Apr. 15-16, 1947	1.24	0.77	2.01	0.79	- - - -	0	- - - -
109	May 21, 1947	1.04	0.56	1.60	1.09	- - - -	0	- - - -
123	May 21, 1947	0.62	0.49	1.11	1.10	13 52	0.26	14 19
113	May 21, 1947	0.80	0.49	1.29	1.12	14 07	0.01	14 30
109	May 25, 1947	1.33	0.98	2.31	1.42	- - - -	0	- - - -
123	May 25, 1947	1.13	0.98	2.11	1.35	11 43	0.28	- - - -
113	May 25, 1947	1.27	0.98	2.25	1.38	12 10	0.01	- - - -
109	June 2, 1947	1.36	1.0	2.36	0.94	- - - -	0	- - - -
123	June 2, 1947	1.12	1.02	2.14	0.87	- - - -	0	- - - -
113	June 2, 1947	1.37	0.98	2.35	0.95	18 51	0.003	- - - -
109	June 6-7, 1947	1.36	0.97	2.33	1.35	22 35	0.002	- - - -
12.	June 6-7, 1947	1.21	0.77	1.98	1.32	22 39	0.16	22 43
113	June 6-7, 1947	1.36	0.88	2.24	1.25	22 35	0.21	23 03
109	July 18, 1947	1.99	1.46	3.45	1.32	- - - -	0	- - - -
123	July 18, 1947	1.87	1.60	3.47	1.30	- - - -	0	- - - -
113	July 18, 1947	1.71	1.32	3.03	1.28	19 25	0.01	- - - -
109	Aug. 16, 1947	1.91	1.78	3.69	1.93	15 00	0.005	- - - -
123	Aug. 16, 1947	1.93	1.50	3.43	1.71	No record	No record	- - - - - - - -
113	Aug. 16, 1947	1.62	1.40	3.02	1.91	15 15	0.14	15 15
109	Aug. 31, 1947	2.61	1.99	4.60	0.62	- - - -	0	- - - -
123	Aug. 31, 1947	2.31	1.89	4.20	0.62	- - - -	0	- - - -
113	Aug. 31, 1947	2.32	1.92	4.24	0.51	01 04	0.01	- - - -
109	Nov. 3-4, 1947	2.72	2.52	5.24	0.97	- - - -	0	- - - -
123	Nov. 3-4, 1947	2.45	2.31	4.76	1.03	- - - -	0	- - - -
113	Nov. 3-4, 1947	2.36	2.24	4.60	0.93	- - - -	0	- - - -

[a] June 16, 1946 Watershed 109 and 123 were in wheat and Watershed 103 was in corn.

[b] Water supply is limiting condition. --Water supply rate so low or storage conditions such that entries would be insignificant.

and 123, and corn Watershed 113 for 1947 and for June 16, 1946

Infiltration rate				Percolation rate at top of subsoil		Transmission rate		
Before water reached subsoil		After water reached subsoil				Topsoil maximum	Subsoil	
From	To	From	To	From	To		From	To
10	11	12	13	14	15	16	17	18
in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
2.22	1.35	1.35	0.49	0.60	0.15	15.0	1.50	0.75
2.06	1.11	1.11	0.04	0.46	0.04	15.0	0.50	0.25
1.95	0.93	0.93	0.05	0.18	0.05	10.0	0.33	0.29
1.2[b]	- -	- -	- -	- -	- -	7.5	- -	- -
0.6	- -	- -	- -	0.6	- -	4.6	- -	- -
1.2[b]	- -	- -	- -	- -	- -	9.1[b]	- -	- -
0.54	- -	- -	- -	- -	- -	3.0	- -	- -
0.13	0.05	0.05	0.04	0.04	0.04	1.0	0.32	0.32
0.41	- -	- -	- -	- -	- -	2.0	- -	- -
0.9[b]	0.30[b]	- -	- -	- -	- -	7.4[b]	- -	- -
1.2	0.04	0.04	0.04	0.26	0.04	3.0	0.57	- -
0.6[b]	- -	0.30	- -	0.33	- -	7.5	- -	- -
0.38[b]	- -	- -	- -	- -	- -	4.6[b]	- -	- -
0.38[b]	- -	- -	- -	- -	- -	3.3[b]	- -	- -
0.24[b]	- -	- -	- -	- -	- -	2.2[b]	- -	- -
0.9[b]	- -	- -	- -	- -	- -	5.5[b]	- -	- -
1.2	0.24	0.24	0.04	0.04	0.04	20.0	0.83	- -
1.8	0.32	0.32	0.06	0.17	0.06	12.0[b]	1.4	0.86
4.6	- -	- -	- -	- -	- -	20.0	1.0	- -
3.0	- -	- -	0.04	- -	0.04	7.5	0.25	0.25
2.7	- -	- -	- -	- -	- -	20.0	- -	- -
1.8[b]	- -	- -	- -	- -	- -	15.0[b]	- -	- -
1.5[b]	- -	- -	- -	- -	- -	12.0[b]	- -	- -
3.0	- -	- -	- -	- -	- -	6.0	- -	- -
6.3[b]	- -	- -	- -	0.37[b]	- -	30.0	- -	- -
7.2	3.0	3.0	0.08	0.12	0.08	30.0	0.77	0.73
5.4	0.41	0.41	0.06	0.13	0.06	20.0	1.1	0.60
4.2[b]	- -	- -	- -	- -	- -	15.0[b]	- -	- -
4.2[b]	- -	- -	- -	- -	- -	15.0[b]	- -	- -
4.2[b]	1.02	- -	- -	- -	- -	15.0	- -	- -
4.0	- -	- -	- -	- -	- -	20.0	- -	- -
4.8		- -	- -	- -	- -	20.0	- -	- -
5.1	2.20	2.20	0.22	0.41	0.10	15.0[b]	- -	- -
2.2[b]	- -	- -	- -	- -	- -	20.0	- -	- -
3.0	- -	- -	- -	- -	- -	20.0	- -	- -
3.0	0.80	- -	- -	- -	- -	8.5	- -	- -
0.9[b]	- -	- -	- -	- -	- -	2.5[b]	- -	- -
0.6[b]	- -	- -	- -	- -	- -	1.7[b]	- -	- -
0.2[b]	- -	- -	- -	- -	- -	0.5[b]	- -	- -

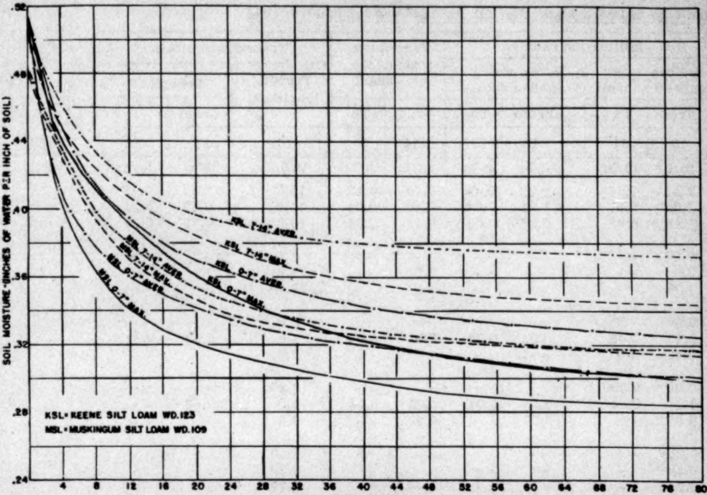

Fig. 2--Maximum and average rates of depletion from saturation to field capacity

Table 3--Storage space available in the soil prior to ground rainfall producing significant runoff, 1947 and June 16, 1946

Date	Watershed No.	Storage space available			Ground rainfall	Runoff
		Topsoil 0-7 inches	Subsoil 7-14 inches	Total 0-14 inches		
		in	in	in	in	in
June 16, 1946	109	2.08	1.70	3.78	3.40	0.47
	123	1.55	1.18	2.73	3.61	1.48
	103	1.35	1.11	2.46	3.65	1.77
Jan. 19-20, 1947	109	0.92	0.56	1.48	1.20	0.002
	123	0.76	0.56	1.32	1.20	0.36
	113	0.84	0.56	1.40	1.23	0.004
Jan. 30, 1947	109	0.98	0.66	1.64	1.12	0.003
	123	0.70	0.51	1.21	1.18	0.38
	113	0.70	0.43	1.13	1.11	0.03
May 21, 1947	109	1.04	0.56	1.60	1.09	0
	123	0.62	0.49	1.11	1.10	0.26
	113	0.80	0.49	1.29	1.12	0.01
May 25, 1947	109	1.33	0.98	2.31	1.42	0
	123	1.13	0.98	2.11	1.35	0.28
	113	1.27	0.98	2.25	1.38	0.01
June 6-7, 1947	109	1.36	0.97	2.33	1.35	0.002
	123	1.21	0.77	1.98	1.32	0.16
	113	1.36	0.88	2.24	1.25	0.21
Aug. 16, 1947	109	1.91	1.78	3.69	0.62	0.005
	123	1.93	1.50	3.43	0.62	no record
	113	1.62	1.40	3.02	0.51	0.14

(2) Rates and amounts of runoff of any significance occur only when the topsoil storage space is exhausted and rainfall rates exceed the percolation rates at the bottom of the topsoil. These percolation rates are limited by the transmission rates in the subsoil. Percolation rates found during 1946 and 1947 have varied from a maximum to a minimum of 0.60 to 0.15 inch per hour for Muskingum silt loam and 0.46 to 0.04 inch per hour for Keene silt loam. The differences between these rates and the rates of rainfall are the supplies available for surface runoff with appropriate corrections for interception storage and depression storage.

(3) After water reaches the subsoil, the rate of exhaustion of the available storage space decreases. This exhaustion occurs approximately in accordance with the infiltration curve or pore size distribution curve as explained in more detail in the previous paper. After the topsoil storage space is exhausted the infiltration rate equals the percolation rate and is governed by it. The constant minimum infiltration rates approached by the soils studied herein are as follows: Muskingum silt loam 0.08, Coshocton silt loam 0.06, and Keene silt loam 0.04 inch per hour. The low rate for Muskingum silt loam is rarely approached whereas the low rates for the other two soils occur more frequently, particularly the Keene silt loam.

Soil properties and land use principally account for differences in hydrologic performance. There appears to be little difference between the rates of water movements in the topsoils of the well-drained soil and the slowly permeable soil. It is believed that this is due to present land use practices. These practices are confined largely to the topsoil. The greatest difference in water movements between the two soil types studied lies in the subsoils. Transmission rates are lower in Keene silt loam due primarily to the greatest number of particles of colloidal dimensions. Another major consideration is the influence of land use upon evapotranspiration. For example, during the early part of the summer, evapotranspiration from corn land is low and soil moisture higher than for other crops such as wheat or meadow. Consequently, space available for the storage of water prior to many storms is low and runoff occurs more readily. Entrapped air is another factor. The prevention of sealing by organic residues and crop roots are likely important factors in promoting high transmission rates. The data on soil properties and interpretations as to the influence of soil properties and land use were previously presented.

The ability of soil to absorb water is a function of the transmission rates within the soil. Whenever the amount of rainfall intercepted by vegetation and retained in depressions is small and there is no runoff, infiltration rates will approximate rainfall rates. Table 4 presents theoretical initial transmission rates required in soil at a given soil moisture to absorb various infiltration rates. The transmission rate of ten inches per hour, shown under the infiltration rate of 3.0 in/hr and opposite a soil moisture content of 0.20 inch per inch of soil or 0.30 inch of available storage space per inch of soil, was computed as follows: The time required to supply 0.30 inch of storage space at an infiltration rate of 3.0 in/hr is 0.30 divided by 3.0 multiplied by 60. This time is six minutes. Since 0.30 represents the available storage space in an inch of soil, water must have moved one or more inches in six minutes and the transmission rate is at least ten inches per hour. Other values were computed accordingly.

The solid stepped line in Table 4 has been placed under all rates of 20 in/hr, the maximum transmission rate generally found for the topsoil of cultivated watersheds at this station. If rainfall rates require a greater transmission rate than the soil moisture content will permit, runoff will occur. For example, during the storm of June 16, 1946, the average initial soil moisture was about 0.30 inch of water per inch of topsoil. Entering Table 4 with 0.30 (Col. 1) and following across the table, the step at 20 is found to be under an infiltration rate of four inches per hour (Col. 13). Depression storage began at $21^h 06^m$ at which time 0.56 inch of rain had entered the soil. A fairly even distribution of this rain in the topsoil brought the soil moisture to 0.38 inch per inch of soil. Entering Table 4 with 0.38 (Col. 1) the interpolated step at 20 represents an infiltration rate of about 2.3 in/hr (Col. 11 and 12). In other words, the topsoil could absorb a rainfall rate of about four inches per hour at the beginning of the storm and a rainfall rate of about 2.3 in/hr at $21^h 06^m$ when depression storage began, as may be seen in Figure 1. Actual rainfall rates were within this range until $21^h 06^m$. After this time, rain began falling at a rate of 2.88 in/hr and detention storage or overland flow began at $21^h 10^m$. Subsequent rates of rainfall were higher causing considerable runoff.

Table 4 also offers an explanation for the low rates and amounts of runoff from small forested Watershed 131. The soil is Muskingum loam. The storm of June 16, 1946 produced a peak rate of runoff of 0.17 in/hr and a total runoff of 0.09 inch from Watershed 131. This was the highest rate and close to the greatest amount in ten years of record. By the time runoff began on June 16 the soil moisture was about 0.40 inch per inch in the upper portion of the soil profile. Beginning at the time runoff began and for a short period thereafter, rates of rainfall were in the vicinity of four or

Table 4--Initial [a]transmission rates required in soil at

Soil moisture per inch of soil	Available storage per inch of soil	Total available storage			Initial transmission rates			
		Topsoil 0-7 inches	Subsoil 7-14 inches	0-14 inches	0.10	0.25	0.50	0.75
1	2	3	4	5	6	7	8	9
in	in	in	in	in	in/hr	in/hr	in/hr	in/hr
0.05	0.45	3.15	3.15	6.30	0.22	0.56	1.11	1.67
0.10	0.40	2.80	2.80	5.60	0.25	0.62	1.25	1.87
0.15	0.35	2.45	2.45	4.90	0.29	0.72	1.43	2.14
0.20	0.30	2.10	2.10	4.20	0.33	0.83	1.66	2.50
0.25	0.25	1.75	1.75	3.50	0.40	1.00	2.00	3.00
0.30	0.20	1.40	1.40	2.80	0.50	1.25	2.50	3.75
0.35	0.15	1.05	1.05	2.10	0.67	1.67	3.33	5.00
0.40	0.10	0.70	0.70	1.40	1.00	2.50	5.00	7.50
0.45	0.05	0.35	0.35	0.70	2.00	5.00	10.0	15.0

[a]Maximum transmission rates for Coshocton soils shown by the symbols below

Subsoil, cultivated crops
Keene silt loam

Subsoil, cultivated crops
Muskingum silt loam

five inches per hour. If rates of infiltration equalled these rates of rainfall, the transmission rates required opposite a soil moisture of 0.40 inch would have been 40 to 50 in/hr. To date, preliminary analyses of forested Watershed 131 indicate a transmission rate of 37.5 in/hr for the topsoil and 7.5 in/hr for the subsoil. Laboratory tests on core samples indicate a transmission rate of 43 in/hr for the topsoil and 15 in/hr for the subsoil. A dashed stepped line has been placed in Table 4 indicating the 40 position. The transmission rates required for no runoff were slightly exceeded in the June 16 storm resulting in the low runoff previously mentioned. It may be seen that the 40 position in Table 4 is exceeded only by intensities that occur rarely. Apparently, this is the reason for low rates and little runoff from forested Watershed 131. However, there is considerable runoff from forested Watershed 172, of which 131 is a sub-drainage. Apparently, the flow is comprised mostly of sub-surface flow. In fact, total yearly runoff has been greater from Watershed 172 than from cultivated watersheds of comparable size, although runoff rates have been lower.

The highest transmission rates found in the subsoil for Keene silt loam and Muskingum silt loam were approximately 0.83 in/hr and 1.5 in/hr, respectively. In Table 4 the limit for Keene silt loam subsoil is represented by the dotted line and the limit for Muskingum silt loam subsoil by the dot and dash line. These transmission rates in the subsoil become the factor limiting infiltration as exhaustion of storage space in the topsoil takes place. With a saturated topsoil and a moisture content of 0.35 inch per inch of subsoil, the maximum infiltration rates that could exist in Keene silt loam would be about 0.10 in/hr. The reason for high percentage of runoff after the exhaustion of storage space in the topsoil is apparent. The maximum infiltration rate that could exist in Muskingum silt loam under similar conditions would be about 0.25 in/hr. The reason for less runoff on Muskingum silt loam is again apparent.

The preceding section dealt with the accretion of soil moisture until runoff occurred, and considered the change in transmission rates within the soil and their effect upon runoff. Soil moisture depletion, due largely to percolation and evapotranspiration, is another important phase of the hydrologic cycle. Figure 2 presents the maximum and average rates of reduction in soil moisture from saturation to field capacity. The data for Figure 2 represent first year meadow, essentially for the period May to October inclusive. These data were obtained from actual measurements of soil moisture, mostly from recording tensiometers. The rate of soil moisture depletion from saturation to field capacity is much greater than from field capacity downward. In the former the loss in moisture is largely due to drainage in which air replaces water in the larger non-capillary pores. The curves simulate the pore size distribution curves for the soils studied. The rate of depletion rapidly diminishes as the curve approaches field capacity and from this point downward much of the depletion is due to evapotranspiration and a replacing of the water in the smaller pores different moisture contents to absorb various infiltration rates

required for infiltration rates in inches per hour of -

1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
10	11	12	13	14	15	16	17	18	19
in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr	in/hr
2.22	4.44	6.67	8.83	11.1	13.3	15.4	17.6	20.0	22.2
2.48	5.00	7.50	10.0	12.5	15.0	17.6	20.0	22.2	25.0
2.80	5.71	8.58	11.3	14.3	17.1	20.0	23.1	26.0	28.6
3.31	6.67	10.0	13.3	16.7	20.0	23.0	26.1	30.0	33.3
3.97	8.00	12.0	15.8	20.0	24.0	28.6	31.6	35.3	40.0
5.00	10.0	15.0	20.0	25.0	30.0	35.3	40.0	46.1	50.0
6.67	13.3	20.0	27.3	33.3	40.0	46.1	54.5	60.0	66.6
10.0	20.0	30.0	40.0	50.0	60.0	69.8	80.0	89.5	100.0
20.0	40.0	60.0	80.0	100.0	120.0	139.5	158.0	183.0	200.0

Topsoil, cultivated crops
Muskingum and Keene silt loam

Topsoil, forest
Muskingum loam

with air. The slower depletion rate reflects the greater force with which water is held by soil as it becomes drier. The average curves represent numerous measurements and are likely applicable to more situations than the maximum. The curves indicate how rapidly storage space becomes available as the soil dries out.

The subsoil curves in Figure 2, which are shown as starting at saturation, generally do not have the same starting time as those in the topsoil. This is due to the fact that percolation at the top of the subsoil takes place as well as at the bottom of the subsoil. The difference between the two percolation rates will determine the rate of increase or decrease of the soil moisture in the subsoil. Generally, the subsoil is not completely saturated during the storm period and available storage space exists. In some cases it becomes saturated after the storm period.

Table 5 was prepared from Figure 2 and summarizes the time required for various average depletions of soil moisture and the development of storage space in the topsoil of Muskingum silt loam and Keene silt loam. The data represent first year meadow and apply to the period May to October inclusive. Table 5 shows, that in a period of 24 hours after saturation is reached, 1.26 inches of storage will develop in the topsoil of Muskingum silt loam and 1.05 inches will develop in the topsoil of Keene silt loam. During the period May to October inclusive, of both 1946 and 1947, the minimum storage available in the subsoil (7-14 inch depth) was 0.56 inch for Muskingum silt loam and 0.49 inch for Keene silt loam. Using the minimum values for the subsoil, the total topsoil and subsoil storage space available 24 hours after saturation of the topsoil would be at least 1.82 inches for Muskingum silt loam and 1.54 inches for Keene silt loam. These quantities may be considered minimum storage amounts. Actually, in only one case for the period May to October inclusive, of both 1946 and 1947, was the storage space prior to any storm less than these amounts. Also, in only one case did the ground rainfall exceed the storage space available in the topsoil and subsoil of either the Muskingum silt loam or Keene silt loam. For all other cases, the storage space exceeded two inches and frequently exceeded three inches.

Table 6 presents the number of storms each year from 1937 to 1947, equal to or exceeding the selected amounts of rainfall shown in the first column. For the entire period of time, on the average, three rains occurred per year which exceeded 1.82 inches and four rains which exceeded 1.54 inches. As mentioned in the preceding paragraph these quantities represent the minimum amounts of storage space that would develop in the 0 to 14-inch depth in 24 hours in Muskingum silt loam and Keene silt loam, respectively. Such rains would produce runoff three times on Muskingum silt loam and four times on Keene silt loam. These are the maximum number of occurrences. Generally, runoff would occur only about once each year, if the storage space in the topsoil and subsoil were used, for the two reasons previously indicated. First, to this storage could be added the amount of water that would percolate below the subsoil. Secondly, only once during the two years investigated did the ground rainfall exceed the available storage space in the topsoil and subsoil.

Table 5--Time required for soil-moisture depletion and storage space development in the topsoil

Elapsed time	Topsoil 0-7 inches			
	Soil-moisture depletion		Storage space development	
	Muskingum silt loam	Keene silt loam	Muskingum silt loam	Keene silt loam
hr	in/in	in/in	in	in
0	0.51[a]	0.51[a]	0.00	0.00
1	0.47	0.48	0.28	0.21
2	0.44	0.46	0.49	0.35
3	0.42	0.45	0.63	0.42
4	0.41	0.44	0.70	0.49
6	0.39	0.43	0.84	0.56
8	0.38	0.42	0.91	0.63
10	0.37	0.41	0.98	0.70
12	0.36	0.40	1.05	0.77
24	0.33	0.36	1.26	1.05
48	0.31	0.33	1.40	1.26
96	0.29	0.31	1.54	1.40

[a] Saturation

For the entire record shown in Table 6, the shortest period of time found between any two storms greater than 1.54 inches was two days. The amount of rain that fell in these two days was insufficient to deplete storage space below the minimum storage values of 1.82 and 1.54 inches.

The preceding indicates that runoff would occur only about once each year between May and October, if transmission rates were great enough to permit use of the storage space in the subsoil as they do in the topsoil. Practices which might increase the transmission rates in the entire subsoil are being investigated at Coshocton. There are about seven inches of topsoil. Practices which would increase the effective depth of topsoil to about ten inches would establish a minimum storage space within 24 hours after saturation of about 1.80 inches in the topsoil of Muskingum silt loam and about 1.50 inches for Keene silt loam for the period May to October. From Table 6 it may be seen that runoff would occur only three times on Muskingum silt loam and four times on Keene silt loam, if no use whatsoever were made of the storage space in the subsoil. Actually, some use is made of this storage space and runoff would occur only once or twice from a topsoil whose depth is ten inches.

Table 6--Number of storms equal to or exceeding selected amounts of rainfall, 1937-1947

Selected amount of rain	Number of storms equal to or exceeding selected amounts of rainfall											Average annual
	1947	1946	1945	1944	1943	1942	1941	1940	1939	1938	1937	
in												
0.25	42	40	56	39	45	46	39	48	42	45	50	44.7
0.50	22	23	29	19	22	24	25	34	22	26	27	24.8
0.75	18	14	17	14	15	14	16	22	13	13	19	15.9
1.00	9	11	11	7	5	7	12	15	9	6	14	9.6
1.25	4	7	6	2	3	5	9	9	5	5	9	5.8
1.50	3	4	6	0	3	4	8	7	4	2	5	4.2
1.75	2	3	4	0	1	3	7	3	4	1	4	2.9
2.00	1	1	4	0	0	3	6	2	3	1	4	2.3
2.50	0	1	3	0	0	3	1	1	3	0	2	1.3
3.00	0	1	1	0	0	0	0	0	0	0	1	0.3
3.50	0	0	0	0	0	0	0	0	0	0	1	0.1

Both soil properties and land use exert marked influences on the transmission rates in soils. However, land use has an important effect upon soil properties. Whenever feasible, consideration should be given to deep-rooted crops that penetrate the subsoil. This would not only promote the development of organic matter in the subsoil, but in addition, transmission rates appear to be greater in the vicinity of the root zone. Mechanical means of ripping the subsoil is another consideration. Both vegetal and mechanical practices which might increase transmission rates in the subsoil are being investigated at Coshocton.

Summary and conclusions--Various storms have been analyzed to study the rates of soil-water movement, particularly as they effect surface runoff. Transmission and percolation rates and the depletion of storage space within the soil were evaluated for watersheds under natural conditions. Soil type and land-use effects were contrasted. The maximum and average rates of depletion from saturation to field capacity were determined for the two major soil types in this area. The time required for soil-moisture depletion and storage development was determined. Data were presented showing initial transmission rates required in soil at different moisture contents to absorb various infiltration rates. The information obtained when related to storm patterns will indicate available supplies of water for surface runoff.

The relationships established furnish a means of relating the influence of soil properties and land use to the hydrologic performance of watersheds. They also furnish basic information useful in flood control and other hydrologic studies.

The data obtained can be applied not only to these soils in other localities in the North Appalachian Region but also to soils with similar hydrologic characteristics located in other parts of the country.

Acknowledgments

Grateful acknowledgment is made to Mary K. Royer and Mary Williams for the compilation and graphing of much of the basic data and their high type of cooperation in the preparation of this paper. Acknowledgment is made to D. E. Hall for assistance in calculations and the preparation of infiltration curves and to R. E. Youker for assistance in soil-moisture determinations.

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(Manuscript received April 29, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

INTERPRETATION OF SNOW SURVEYS

Walter U. Garstka

Abstract--A method is presented for the forecast of seasonal water yield based upon snow-survey data. The method takes into account snow water equivalent by area-elevation zones, and interpolates derived snow water equivalents for higher altitudes and for other parts of a watershed not actually sampled by snow courses. The effectiveness of the method is evaluated by statistical analysis.

The accuracy of forecasts of seasonal water yield could be improved by either increasing the number of snow courses, or by refining methods of interpretation of snow-survey data, or, in most cases, both. The following method of calculation of water equivalent in storage on a drainage basin is based on the assumption that a snow course is a sample of the snow water equivalent at that elevation, aspect, and vegetation, if any. This concept of elevation-weighting of snow data was used in connection with the analysis of one of the great floods of the Clinch River, on which the Norris Dam is located in Tennessee [GARSTKA, 1946].

Elevation-weighting of snow-course data is based upon the common observation that the amount of snow accumulation increases with altitude. This is a result of two climatological processes. Precipitation tends to fall as snow at higher altitudes because of the cooling effect on uplifts of air induced by mountain ranges. Prevailing lower air temperatures at higher altitudes tend to preserve the snow blanket until spring. It is recognized that the depth of snowfall and of snow accumulation is influenced by factors other than elevation. Among these may be listed the differences in precipitation caused by geographic size of the drainage basin, by local orographic and barrier effects, by aspects, and by prevailing storm paths. The accumulation of snow on the ground at given points may be influenced considerably by prevalence and type of forest growth.

Figure 1 shows the relationship between snow water equivalent and elevation. The Snake River drainage basin, as shown in Figure 2, is considered in two subdivisions in this paper. Snake River above Jackson Lake, Wyoming, refers to that portion of the drainage basin which flows into Jackson Lake; seasonal water volumes, expressed in acre feet, have been corrected for changes in storage at Jackson Lake, and express, therefore, the yield from the melting of the accumulated winter season's precipitation. Snake River, Jackson Lake, or Moran, Wyoming, to Heise, Idaho, refers to that part of the drainage basin above Heise, Idaho, but exclusive of the drainage basin above Jackson Lake, Wyoming. The runoff totals given for this part of the Snake River drainage basin do not include the water yield of the Jackson Lake drainage basin.

The curves of Figure 1 show a very definite trend of increase of snow water equivalent with altitude. A good geographic distribution of the snow-course locations, as shown in Figure 2, and the existence of the altitudinal trend permits the treatment of snow courses as samples of the snow cover within the watershed. The position of the individual snow-course plottings vertically on Figure 1 can be interpreted to indicate the relationship with reference to elevation. Horizontal displacement, or differences of snow water equivalent among courses at or about the same altitude, reflects the effects of geographic location, storm paths, and factors other than elevation. A curve through the points averages snow accumulation both horizontally and vertically and thus expresses the average snow water equivalent for the watershed. All of the Jackson Lake snow courses are found in a narrow band of elevations ranging from 6780 to 7900 ft. Since the Jackson Lake drainage basin is within the Snake River basin above Heise, all snow courses within the watershed above Heise were used in calculating the snow water equivalent for the watershed below Jackson Lake and above Heise. Only the courses above Jackson Lake were used for the Jackson Lake basin forecasts.

In order to reduce office work, charts similar to Figure 1 were not plotted for each month for each year. Instead, average elevation and average snow water equivalent points were computed for broad elevation ranges. These points served as a guide for delineation of the curve, as is shown in Figure 3.

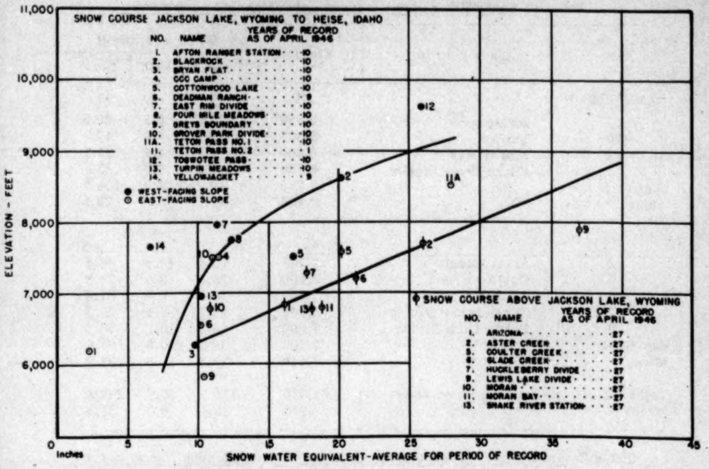

Fig. 1--Snake River, Idaho and Wyoming, snow in relation to elevation

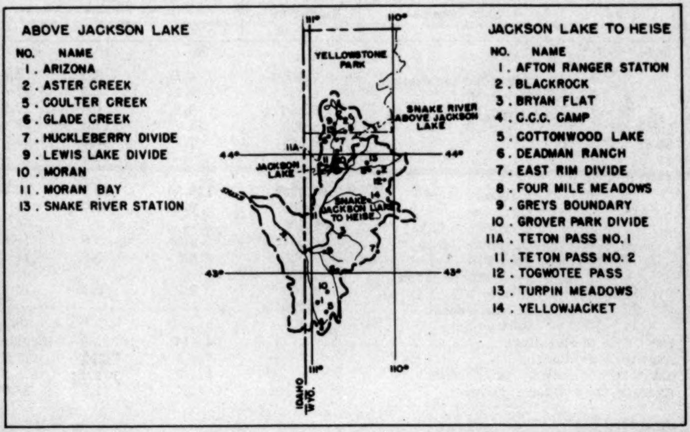
ABOVE JACKSON LAKE
NO. NAME
1. ARIZONA
2. ASTER CREEK
5. COULTER CREEK
6. GLADE CREEK
7. HUCKLEBERRY DIVIDE
9. LEWIS LAKE DIVIDE
10. MORAN
11. MORAN BAY
13. SNAKE RIVER STATION
JACKSON LAKE TO HEISE
NO. NAME
1. AFTON RANGER STATION
2. BLACKROCK
3. BRYAN FLAT
4. C.C.C. CAMP
5. COTTONWOOD LAKE
6. DEADMAN RANCH
7. EAST RIM DIVIDE
8. FOUR MILE MEADOWS
9. GREYS BOUNDARY
10. GROVER PARK DIVIDE
11A. TETON PASS NO. 1
11. TETON PASS NO. 2
12. TOGWOTEE PASS
13. TURPIN MEADOWS
14. YELLOWJACKET
111°
110°
YELLOWSTONE PARK
SNAKE RIVER ABOVE JACKSON LAKE
44°
44°
11A
JACKSON LAKE
SNAKE JACKSON LAKE TO HEISE
12
14
43°
43°
111°
110°
IDAHO
WYO.

Fig. 2--Location of snow courses in Snake River drainage basin above Heise, Idaho

The Jackson Lake snow courses were averaged in two classes: Under 7000, and over 7000 ft. An example of this computation is given in Table 1. Snake River between Jackson Lake and Heise snow courses were averaged in three classes: under 6500 ft; 6500 to 8250 ft; and over 8250 ft. It was noticed that all of the courses above Jackson Lake fall into the 6500 to 8250-ft class. To simplify calculations, totals of elevations and of water equivalents were transferred from Table 1 to Table 2, the latter being an example of the average point calculation for the Snake River between Jackson Lake and Heise.

Table 1--Snake River above Jackson Lake, March 1 snow survey

No.	Snow course	Elevation	Water equivalent		
			1945	1944	1943
under 7000 ft		ft	in	in	in
1	Arizona	6,850	12.5	6.5	25.5
10	Moran	6,800	9.2	4.0	17.3
11	Moran Bay	6,800	12.3	8.6	33.1
13	Snake River Station	6,780	15.2	7.9	28.8
Sub-total		27,230	49.2	27.0	104.7
Mean		6,808	12.3	6.8	26.2
over 7000 ft					
2	Aster Creek	7,700	16.4	11.6	46.4
5	Coulter Creek	7,600	16.4	9.6	33.7
6	Glade Creek	7,200	16.6	8.4	31.8
7	Huckleberry Divide	7,300	13.7	8.1	27.3
9	Lewis Lake Divide	7,900	26.0	16.2	55.4
Sub-total		37,700	89.1	53.9	194.6
Mean		7,540	17.8	10.8	38.9
Total for all nine courses listed above		64,930	138.3	80.9	299.3
Mean		7,210	15.4	9.0	33.3

Table 2--Snake River between Jackson Lake and Heise, March 1 snow survey

No.	Snow course	Elevation	Water equivalent		
			1945	1944	1943
under 6500 ft		ft	in	in	in
1	Afton Ranger Station	6,200	4.7	3.2	5.5
3	Bryan Flat	6,250	7.7	3.2	17.4
9	Greys Boundary	5,800	9.1	4.9	15.5
Sub-total		18,250	21.5	11.3	38.4
Mean		6,083	7.2	3.8	12.8
6500 to 8250 ft					
	Jackson Lake[a]	64,930[a]	138.3[a]	80.9[a]	299.3[a]
4	CCC Camp	7,500	9.4	5.9	14.2
5	Cottonwood Lake	7,500	.....	.....	.....
6	Deadman Ranch	6,534	8.9	2.9	19.8
7	East Rim Divide	7,950	6.8	5.8	15.9
8	Four Mile Meadow	7,770	.....	.....	.....
10	Grover's Park Divide	7,500	8.2	6.1	13.9
13	Turpin Meadow	6,930	.....	.....	.....
14	Yellow Jacket	7,675	.....	1.0	10.1
Sub-totals of elevations			94,414	102,089	102,089
Average elevations			7,263	7,292	7,292
Sub-totals of snow water equivalent			171.6	102.6	373.2
Average snow water equivalent			13.2	7.3	26.7
over 8250					
2	Blackrock	8,600	.....	.....	.....
11-a	Teton Pass 1	8,500	18.6	12.0	42.4
11	Teton Pass 2	8,500	24.1	.....	.....
12	Togwotee Pass	9,600	.....	.....	.....
Sub-total		8,500	42.7	.....	.....
Mean			21.4	12.0	42.4
Number of courses			18	18	18

[a] Transposed sub-totals for nine snow courses above Jackson Lake from Table 1.

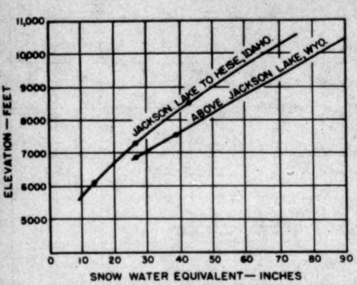

Fig. 3--Snake River, relation of snow storage to elevation as of March 1, 1943

Average points calculated in Tables 1 and 2 were plotted as shown in Figure 3. Curved lines were drawn through the three points for the Snake River between Jackson Lake and Heise. It was observed that for some years these lines were concave, for others, convex. No two years produced the same shape of curve having the same slope for the same nominal date of the survey, as is shown in Figures 4 and 5. Curves differed for the same year as based upon February, March, and April 1 surveys, as is evident in Figure 6. Not enough courses were surveyed to permit the construction of comparable curves as of May 1. In a few instances, as of February 1, 1940 and 1941, the curves plotted almost vertically, indicating much greater water equivalent storage at lower than at higher altitudes.

Snow packs at centered low elevations are known to result in early snow melts, and are apt to produce high rates of runoff. Differences among storage-elevation curves may serve to explain why most efforts at more precise statistical correlation analyses of data from individual snow courses have not yielded as promising results as is ordinarily expected of such analytical techniques. In the absence of any high-altitude snow courses above Jackson Lake, there are no data to determine whether the curve should be concave or convex. Under the circumstances, a straight line was drawn through the two average points for the area above Jackson Lake.

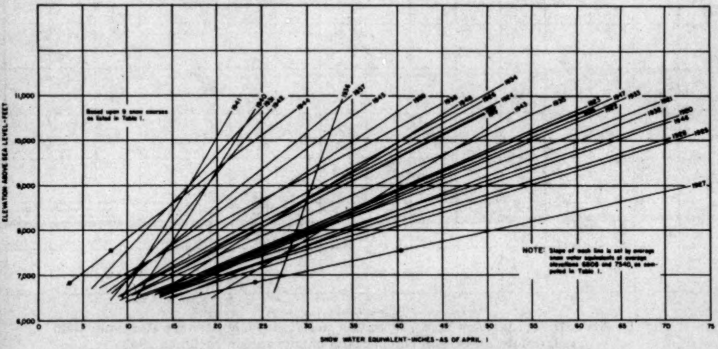

Fig. 4--Snake River above Jackson Lake, Wyoming, snow water equivalent in relation to elevation, 1919-1948

A map of the two drainage basins was planimetered and area-elevation relationships were computed. This information is given graphically in Figure 7. The idea of applying an elevation factor to snow surveys is not new. CHURCH [1942] mentions it in connection with forecasting at Lake Tahoe, California-Nevada. BEAN and THOMAS [1940] applied an area-elevation correction to the snow surveys in the Androscoggin River basin in Maine. SALO [1940] developed the mean-elevation concept for estimating the snow storage in the Merrimac River basin in New Hampshire rapidly. The method of elevation-weighting snow-survey data presented in this paper differs from others in that it uses individual snow courses to establish the curve of snow storage in relation to elevation. Water equivalent values are derived from this curve and used in connection with area-elevation distribution fractions to compute the elevation-weighted snow water equivalent for the drainage basin, thus taking into account portions of the drainage basin not sampled by snow surveys. Table 3 illustrates this method of computation. In this table, fractions of area are derived from Figure 7, and snow water equivalents for elevation classes from the March 1, 1943, curve of Figure 6.

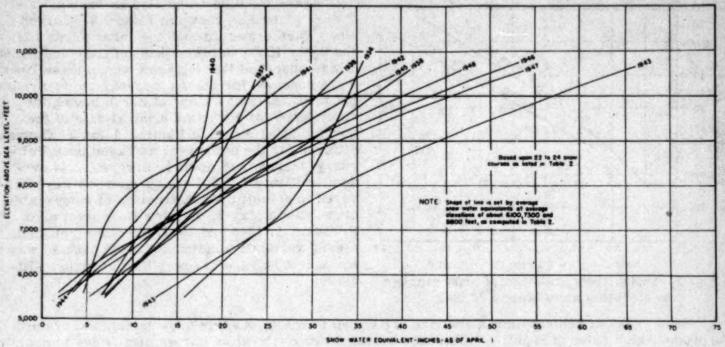

Fig. 5--Snake River, Jackson Lake, Wyoming to Heise, Idaho, snow-water equivalent in relation to elevation, 1936-1948

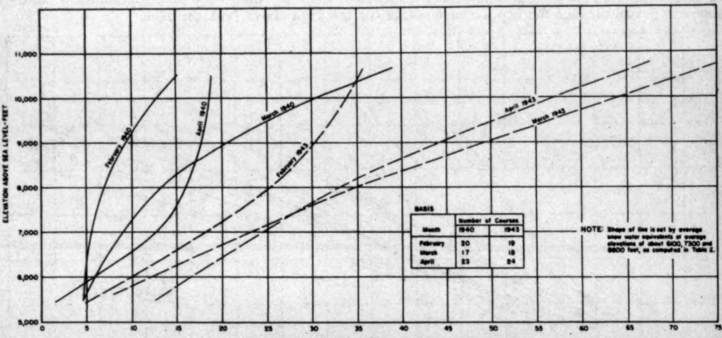

Fig. 6--Snake River, Jackson Lake, Wyoming to Heise, Idaho, snow water equivalent in relation to elevation, comparison of curves for 1940 and 1943

The snow-course records above Jackson Lake are unusual not only in the length of their record, but also in their completeness. They were first established and are maintained and surveyed by the United States Bureau of Reclamation. In 1936 they were incorporated into the West-wide system of snow surveys coordinated by the Division of Irrigation of the Soil Conservation Service, when the snow courses were staked out in the standard manner.

Figure 8 shows a regression-line type of forecast chart based upon simple arithmetic averages of snow courses above Jackson Lake, Wyoming. Figure 9 is a similar chart for the Snake River between Jackson Lake (Moran) and Heise. Figures 10 and 11 are for the respective watersheds, the correlation being based upon elevation-weighted snow water equivalents.

Figures 8 and 10 present two sets of mean and upper and lower limit lines. The solid lines are for the period beginning with 1936, when the snow-course network was incorporated into the West-

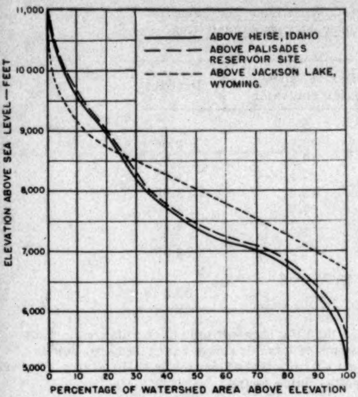

Fig. 7--Snake River, area-elevation relationship

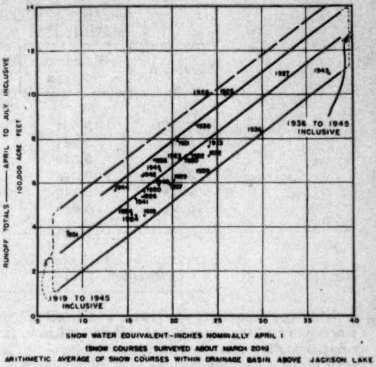

Fig. 8--Snake River above Jackson Lake, arithmetic average of snow courses

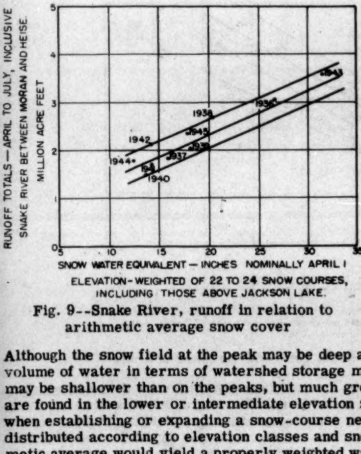

Fig. 9--Snake River, runoff in relation to arithmetic average snow cover

wide system. The dashed lines are for the period of record, beginning with 1919. Only the accumulation of records in the future can disclose which of these two sets of lines most nearly reflects the relationship of snow storage to runoff in the drainage basin above Jackson Lake. The Grand Teton Mountains are found in the drainage basin of the Upper Snake River above Heise, Idaho. This range is among the great mountain ranges of the Continent. The higher elevations have been practically inaccessible in the winter because of vast distances and steep slopes. Mechanized over-the-snow transport and aircraft should be of real value in providing access to snow courses in this and similar areas.

By far the greatest fraction of the cost of performing a snow survey is that expended on travel time to and from a snow course. Where present courses are located at high altitudes, additional courses could be surveyed at low and intermediate altitudes at very slight increase in total cost. Although the snow field at the peak may be deep and may stand out prominently, a much greater volume of water in terms of watershed storage may repose at intermediate altitudes. The snows may be shallower than on the peaks, but much greated percentages of total drainage basin area are found in the lower or intermediate elevation zones, as shown in Figure 7. It should be possible, when establishing or expanding a snow-course network, to locate the courses so as to have them distributed according to elevation classes and snow accumulation zones, so that a simple arithmetic average would yield a properly weighted watershed value.

Figure 12 shows the percentages of snow appearing as runoff in the Snake River above Jackson Lake, Wyoming. It is to be noted that the points for low-volume water-yield years exhibit a very high percentage of snow water equivalent appearing as runoff, whereas the large-volume water-yield years exhibit a considerably lower runoff-yielding effectiveness. This unanticipated relationship may be explained in part by reference to Figure 4. Small runoff-volume years, 1931, 1940, 1941, 1942, and 1944 were years of low snow storage at both low and high elevations, while large runoff-volume years 1925, 1927, and 1928 were years of heavy snow accumulation at both low and high elevations. It is possible that the low-altitude snow packs were subjected to earlier

Table 3--Snake River between Jackson Lake and Heise, elevation weighted snow-storage computation, March 1, 1943

Elevation	Fraction of area	Derived snow water equivalent	Product
		in	
5,800	0.067	10.0	0.67
6,500	0.261	17.2	4.49
7,500	0.379	29.1	11.03
8,500	0.094	42.4	3.99
9,500	0.140	57.5	8.05
10,500	0.059	73.3	4.32
Totals	1.000	. . .	32.55
Elevation-weighted snow water equivalent as of March 1, 1943			32.5 in

melting and especially to greater evaporation losses than the high-altitude accumulations. Thus, since more of the snow lay at higher altitudes, in terms of total drainage basin storage, during small runoff-volume years, it was subjected to less loss and, therefore, the runoff yielding effectiveness of the snow was greater than during large runoff-volume years.

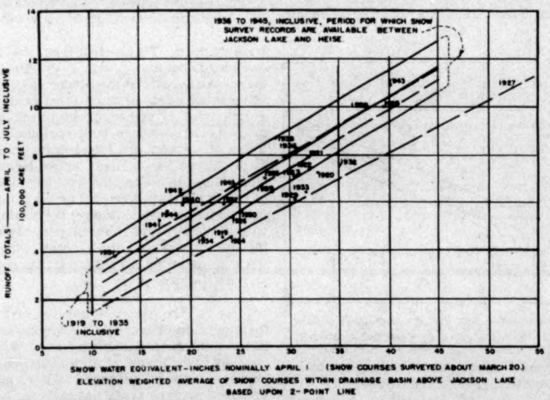

Fig. 10--Snake River above Jackson Lake, elevation-weighted average

Conclusions--For the arithmetic average-based forecast (see Fig. 8) for the Snake River above Jackson Lake, Wyoming, the correlation coefficient is 0.760 + 0.086, whereas for the elevation-weighted average based forecast (see Fig. 10), the correlation coefficient is 0.824 + 0.066. Correlation coefficients were not calculated for the forecasts on Figures 9 and 11, because of the few years of record for snow surveys in the Snake River drainage basin between Jackson Lake, Wyoming and Heise, Idaho.

The forecast for the Snake River above Jackson Lake, Wyoming, (see Fig. 10) derived statistically can be expressed

$$Y = 154.3 + 19.2\,X$$

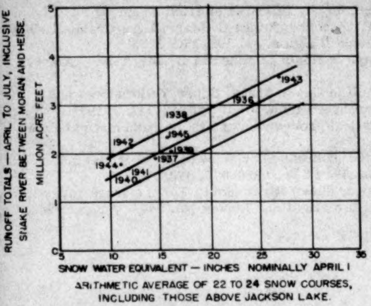

Fig. 11--Snake River, runoff in relation to elevation-weighted snow cover

in which Y equals April to July, inclusive, inflow to Jackson Lake, Wyoming, in units of 1000 ac ft; and X equals the elevation-weighted snow water equivalent, based upon nine snow courses in the watershed above Jackson Lake, expressed in inches, as of April 1.

Acknowledgments--This paper reports, in part, an investigation performed in the Hydrology Division, J. R. Riter, Chief; Branch of Project Planning, Bureau of Reclamation, U. S. Department of the Interior. Assistance of Murry I. Balogh, Clinton A. Bernard, Clarice L. Dorrance, Dessie Fontecchio, and Harry Hepting in the performance of the investigation, and of Perry M. Ford for statistical consultation is gratefully acknowledged.

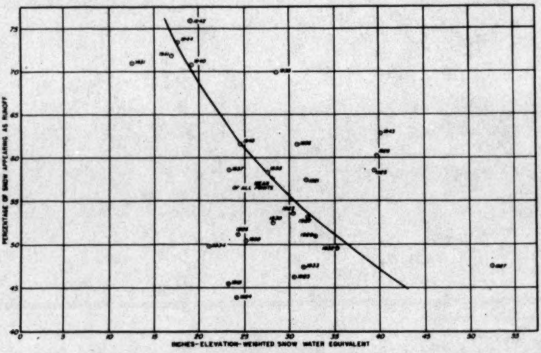

Fig. 12--Snake River above Jackson Lake, Wyoming, runoff-yielding effectiveness of snow

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United States Department of the Interior,
Denver, Colorado

(Manuscript received July 1, 1948; presented at the Pacific Northwest Regional Meeting, April 21, 1947; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

SOLIDS IN STREAM FLOW

Gerard H. Matthes

Abstract--The natural solids load has a stabilizing influence on the maintenance of stream channels. Its importance in this respect entitles it to recognition in the definition of regimen. Channel deterioration results whenever changed watershed conditions or the works of Man, operate to produce marked changes in the solids load, either as to volume or character. Dissolved solids are of far greater importance in sedimentation than is commonly supposed. They should be recognized as a definite part of the sediment load, being subject to settling out through chemical reaction and by evaporation. Flocculation of clays and collodial matter by sea water constitutes one of the most serious economic problems in estuaries and harbors. European rivers afford numerous examples of irreparable damage to river beds and banks occasioned by unwise streamflow regulation by reservoirs and channel regularization; also by sedimentation in reservoirs. Regrettable conditions of this kind are making themselves manifest in many parts of the United States. The need for more foresight in the utilization of our water resources is indicated, lest future generations be faced with irreparably damaged streams.

The wish, so often expressed by nature lovers and over-solicitous conservationists, to the effect that soil wash from the land should be prevented to the extent that streams may flow clear water at all times, is not founded on sound doctrine. A certain amount of sediment is needed by streams to maintain their channels. The amount of sediment load so required varies widely as between streams, depending upon watershed conditions and climate, and is undefinable except as it may be designated by the term "natural load." Usually largest in proportion to water discharge during high stages, the natural load may dwindle to zero during extreme low stages, and may even become a negative quantity when silt and fine sand are blown out of dry river beds, a common occurrence in western stream beds. But, whatever characteristics the natural load may assume in individual cases, its function is indispensable as a stabilizing agency in the maintenance of natural channels. In the absence of this natural load, as for instance where sedimentation in a large reservoir robs a stream of its load, the desilted waters issuing from the reservoir build up a new load by eroding the stream bed. Conversely, excessive soil erosion, that is, erosion in excess of natural rates, operates to overload streams. In either case, stream channel deterioration ensues, usually followed by a sequence of ruinous conditions which are extremely costly to rectify and in many instances are not correctable.

In the nature of things, channels in earth, are not suited for the conveyance of clear water under variable-flow conditions. This applies as much to artificial channels as it does to natural channels. Thus, in irrigation canals and ditches a certain amount of silt or very fine sand, is found beneficial for checking erosion and in reducing seepage losses. From the Imperial Valley in California, where of recent years desilted water has proved helpful in reducing the cost of ditch cleaning, now comes the complaint that the elimination of the silt has resulted in increased seepage losses, which in turn call for costly enlargements of drainage canals. Another disturbing result of the use of desilted water there has been the accelerated growth of aquatic mosses, which previously did not prosper in turbid water, but now require constant removal in order to maintain discharge capacity.

Stream regimen--The indispensable function of the natural load in streams, thus far, has received no recognition in the rather vague present-day definitions of stream regimen. The following definition is proposed: Regimen connotes the control over runoff and erosion imposed by climatic and undisturbed watershed conditions, that enables a stream to fashion and maintain a channel having a discharge capacity adjusted to the fluctuations normally occurring in its water discharge and solids load. Regimen, so defined, applies to torrential streams as well as to tranquil-flow streams. The concept applies to the channel; not to any stream as a whole. Each stretch of a river is controlled by a regimen of its own. This regimen, and therefore the channel characteristics, usually change noticeably (a) below the mouth of any tributary of importance owing to the modifying influences introduced by additional water and solids; (b) with each major change of gradient in the stream's profile; (c) with each major change in the geological formations traversed. A stream channel is said to be "in regimen" with the forces that act upon it when it has reached a quasi-stable form which, though subject to minor variations, always tends to reassert itself.

Stream channels, of all types, deteriorate during the intervals between high stages. The character and extent of such deterioration varies widely as between streams, affecting the heavy sediment carriers more than the less burdened ones, but operates invariably to shrink the discharge capacity. In some rivers this results largely from coarse sediment, brought in by tributaries, which the main channel is unable to clear except during flood stages. Such deposits form bars and islands which obstruct flow and in many instances become covered with vegetation which, in turn, promotes further deposition to take place. In rivers carrying heavy burdens it is a matter of common observation that during a succession of years producing less than average high stages, the channel capacity becomes reduced to such an extent that the first ensuing major flood then rises to stages appreciably higher in ratio to discharge than normal. After such a major flood, much, if not all of the lost channel capacity is usually regained owing to flushing action. Movable-bed streams afford numerous illustrations of these alternating shrinkage and enlargement processes. The Lower Mississippi River, which has been the subject of exhaustive studies, affords examples on a large scale. In this river, a given high-water discharge, selected well within banks registers from one to two feet higher during a major flood that follows a two- or three-year period devoid of high stages, than the same discharge registered prior to the lean period. (Differences in discharge corresponding to one foot of gage height at bank-full stages amount to about 60,000 cfs.) It usually requires a succession of several high-water years to reduce flood stages to normal height. The channel capacity lost during the lean period is thus gradually regained. Regimen, however, is not to be regarded as immutable. Its constancy, under strictly natural conditions, is apt to be over-rated, since the controlling conditions, namely watershed and climate, themselves, are subject to slow but progressive changes. In marked contrast are the rapid changes consequent on Man's occupancy of watersheds; on his utilization of surface waters for a variety of purposes, of which diversions from one watershed to another, sewage disposal, irrigation uses, and flood control are but a few. Even more disturbing are the often unpredictable consequences that result from accelerated watershed erosion, precipitated by denudation, unwise land uses, timber cutting, and forest fires. These throw increased sediment burdens on streams, that upset regimen relations drastically.

The foregoing statements are not to be interpreted as signifying that large flood flows are an important factor in river regimen as regards maintaining channel capacity. They are not. The most efficient reconditioning of stream channels takes place during periods of bank-full, or near bank-full flow. By contrast, great floods, as a rule, are apt to be more harmful than beneficial. It may be inferred, therefore, that conservation methods will be promoted by reducing flood discharge to within-banks proportions rather than by trying to abolish floods altogether.

Chemical sedimentation--The rather widespread belief that the word sediment applies only to fragmental mineral matter that settles out by gravity, is not well founded, and is not supported by dictionary definitions (see Appendix I). It ignores the fact that solids transported in solution enter into and become parts of every fragmental sediment deposit, due to the mere fact that each fragmental particle carries with it, in settling, a film of water containing solids in solution. These eventually crystallize out in solid form. Although not so readily visualized in our eastern streams, impressive illustrations are afforded by the streams of our arid western states, which carry heavy dissolved loads, at times heavier than their suspended loads. Efflorescences and incrustations of so-called "alkali" salts are commonly seen along river banks, on bars, and even on dry river beds. The tonnage of dissolved solids transported by many western streams is extraordinarily large. The Colorado River at Yuma, before the construction of high dams on that stream, carried a dissolved concentration which averaged from 500 to 600 ppm annually, a figure which equals the average annual suspended concentration in the Lower Mississippi River. During low water the concentration ran as high as 1000 to 1700 ppm or about the same as the suspended concentration in the Mississippi during floods.

Sandstones, shales, and conglomerates are known as sedimentary rocks. These contain, on examination, chemical matter that was held in solution at the time the original deposits were made. In some cases, it played an important part in the cementation that turned the deposit into stone. With the spread of civilization the dissolved load has come in for increasing attention. It is beyond the scope of this paper to make mention of the numerous instances in which dissolved matter disqualifies river water for use in a variety of industrial processes. These, together with the contamination resulting from mine effluents, oil fields, industrial wastes, and sewage, are too well known to need rehearsing. Worthy of emphasis, however, is the value of the dissolved solids in maintaining the fertility of flood-plain and delta lands. This is particularly true in areas of heavy annual rainfall, as for instance in the lowlands of Alabama, Louisiana, and Mississippi. Heavy rains, there, remove from the soil annually large quantities of soluble plant food. Overflow by flood waters is the replenishing agency provided by Nature. In this connection, the soluble ingredients in river waters are of more direct value than are the fragmental solids. These latter first require disintegration by sunlight and bacterial activity before portions of them can be assimilated by plant roots. Fertile land in the alluvial valley of the Lower Mississippi River in localities that have long been protected against overflow by high levees, has declined in productivity, whereas the unprotected areas and lands overflowed by levee failures continue to grow big crops. (The late Wm. Gerig, Head Engineer, Office of the Chief of Engineers, Washington, D. C., stated to the writer that his father's farm near Arkadelphia, Arkansas in earlier days produced cotton at the rate of a bale to the acre. Complete protection against over-flow gradually reduced production to half a bale to the acre. Similar reports have been received from sections of the Yazoo River country.) In Egypt, where the mud of the Nile is the subject of religious worship, the irrigators, some years ago, protested when British engineers informed them that Nile water, desilted by storage in reservoirs, still carried an abundance of fertilizing elements for their crops. No such apprehensions have been entertained in the United States, thanks to the educational information dispensed by the Department of Agriculture.

Well known are the damaging effects on vegetation and on concrete, of the western "alkali" salts. Less well known is the fact that one part per million of boron salts renders irrigation water unfit for citrus groves. In the case of long rivers like the Platte and the Rio Grande, seepage waters from irrigated lands return to the river loaded with additional dissolved matter derived from their journey underground. The extensive re-use of these seepage waters is receiving considerable attention by both United States and Mexican engineers [see Annual Water Bulletins issued by the International Boundary and Water Commission, United States and Mexico, El Paso, Texas].

Our eastern rivers also present chemical problems apart from those relating to sewage and industrial wastes. In several sections of the East, tannic acid leached from the roots of vegetation, coats stream-bed materials with tannates so thoroughly as to render them unfit for use as concrete aggregates. In the estuaries and harbors of the South Atlantic and Eastern Gulf coasts, the chemical action of salt water on the clays and colloidal gels brought down by the rivers, causes flocculated deposits to form on a vast scale, so vast, in fact, as to call for their removal by dredging in terms of millions of cubic yards annually in order to maintain navigable depths. Nor does all that is so removed constitute the total deposited by flocculation; a large part is swept out to sea by ebb-tide currents. Flocculation is an electro-chemical process of base-exchange analogous to that which takes place in the reconditioning of zeolites in water-softening plants. There results a hydrous silicate of aluminum with a sodium base, whose particles at once form nuclei which settle out. In simple language, what at first was a calcium clay turns into a sodium clay. The red color fades to a yellowish-gray and eventually to a bluish gray. The deposits so formed partake at first of the nature of a sludge (mud to the layman) which still permits a sounding lead to penetrate and touch bottom, but which offers considerable resistance to the passage of hulls and propellers of ships. If permitted to accumulate and lie undisturbed, compaction takes place resulting in a stiff dark blue clay known to engineers and geologists as marine clay. Deposits of this kind are abundant in stratified rocks as far back as the earliest. Marine clay is recognized as a sedimentary formation. The conclusion is inescapable that the chemical constituents of a river's load are of a sedimentary nature, being subject to deposition by any one of several processes, and should therefore be classified as part of the sediment load. Its exclusion from the definition of sediment, heretofore, not only has been incompatible with the concurrent use of the term sedimentary formations as applied to stratified formations composed of materials laid down by water, but has been inconsistent with dictionary definitions. From the foregoing, it will be seen that the dissolved solids load is a factor to be reckoned with, being at times of great value, or again definitely harmful.

Relative importance of water and sediment--The question naturally arises as to which of these two factors, water discharge or sediment discharge, is the more dominant and therefore has greater economic significnace. In the long run, they appear to be well matched, so long as their relative proportions, through the seasons, remain substantially unaltered, but available evidence leads to the conclusion that any sustained increase or decrease of load, as a rule, is more detrimental to stream channels than manipulation of the water discharge. Differently stated, by far the greater number of troublesome engineering and economic problems concerned with streams and their utilization, have been caused by interference with the natural rate of sediment movement. The older countries were among the first to learn severe lessons in this respect. Scrupulous care of land use was often carried to extremes. It has been common practice in many European countries, after a heavy rain, for farmers to carry many hod-fulls of soil uphill in order to replace soil washed from their fields. The rebuilding of impoverished soil with better quality soil retrieved from rivulets and river banks has been common practice there. But, however excellent all these methods proved in combatting soil losses, much permanent damage was done to stream channels, both large and small, owing to carrying stream regulation plus soil conservation too far. Notably in Germany, channel regularization, and flow regulation by means of storage reservoirs have caused stream beds to scour at an alarming rate. In the Upper Rhine, below Basle, the bed has become lowered as much as 23 ft in the course of 40 years. In the Lower Rhine, as the result of extensive channel contraction works, the under-pinning of bridges, quay walls and other structures along the river has become exposed and is being subjected to severe erosive action. Similar conditions in other German rivers have been aggravated by the interception of sediment at dams and in reservoirs. To arrest further channel deepening, recourse has been had to placing low sills across stream beds, a difficult as well as costly undertaking. A contributing factor on some streams has been the propulsion of barges by poling. This tends to loosen the river bed thereby promoting the washing away of the finer particles. Cutoffs, in some instances, have caused excessive acceleration of velocity and entrainment of river-bed materials, and in certain streams navigable depths have tended to become reduced unduly. Dutch engineers, on the Meuse River, were forced to abandon an ambitious channel rectification program planned for this river, because they found that many stretches would no longer have navigable depths during the low-water season.

In the United States, difficulties with maintaining navigable streams, on the whole, have been few, if we except the tidal portions affected by the flocculation of clays, as previously described. This good record, in large part, is due to this still being a young country, compared with European countries; in part, also, to canalization by locks and dams which still permits flood flow and its sediment burden to pass downstream unhindered. Sedimentation on flowage lands above low dams has made material progress, however, notably above Hales Bar Dam on the Tennessee River, and on the Upper Mississippi above Keokuk Dam.

Heavy sediment-bearing rivers flowing in erodable beds are sensitive to comparatively slight changes by Man. In one instance, channel improvement for navigation on the Upper Mississippi River at St. Louis, was followed by channel degrading which lowered the low-water level at that city by about four feet in the course of ten years. In another instance, the 60-mi stretch between Cairo, Illinois, and New Madrid, Missouri, on the Lower Mississippi River, became affected by minor flood-control works which caused the bed to aggrade, resulting in raising the low-water plane at the mouth of the Ohio River by four feet in a period of 25 years. This case is of particular interest, since the Lower Mississippi, despite its ceaseless meandering, is noted for having maintained previous to the inauguration of the "cutoff" program a stable profile over its 1000-mi length.

Retrogression and aggradation below dams--In Europe and also in British India, engineers early made acquaintance with river-bed retrogression below dams due to interception of the sediment load, and learned the dangers of this long before the subject evoked interest in this country. In practically all cases where bed retrogression reached large proportions, aggrading of the river bed farther downstream caused by coarse bed-load materials dumped in by the tributaries, has been the more serious evil. The concurrent action of retrogression and aggradation amount to a leveling process that flattens hydraulic gradients. Once such conditions reach an advanced state, the channel is damaged usually beyond repair.

In this country, the case of the Rio Grande below Elephant Butte Dam is one of the earliest, and is therefore well known. Only its salient features need be mentioned. Aggrading of the bed, caused by gravel brought in by several uncontrolled tributaries which empty into the river below the dam, was the primary cause of profile flattening. Storage of flood flow by the dam deprived the river of its erstwhile power to erode and transport these sediment accretions. By contrast, erosion of the bed below the dam has been but a minor contributing factor. It was checked by four low diversion dams for irrigation, and to some extent also by the gravel brought in by the tributaries. Aggradation of the river extending downstream to El Paso reached its maximum at the International Dam, and thence continued downstream for some distance. Rapidly mounting damage caused by flash floods from the uncontrolled tributaries referred to, made necessary the construction of Caballo Dam, 30 mi downstream from Elephant Butte. This high dam now effectively controls the floods from these tributaries, and by checking further aggradation has made possible an extensive rectification of the channel below El Paso. These works, all built at great cost, have restored fairly stabilized conditions. Obviously, no small-scale local effort could have remedied the untenable conditions that were created by the channel deterioration.

An entirely different situation has developed on the Colorado River below Hoover Dam since its closure in 1935. The scouring power of the clear water, released on a river-bed slope of 1.5 to two feet per mile, caused extensive erosion. The finer particles were transported great distances down the river, but the coarser materials settled out sooner. In the vicinity of Needles, California, about 100 mi below the dam, aggradation previously had been in progress for many years from natural causes, the rise of the bed amounting to 11 ft in the period 1902-1935. This aggradation became accentuated when, in November of 1938, the backwater from Parker Dam reached the vicinity of Topock, 12 mi below Needles. Bars formed in this backwater which gave rise to dense growths of willows and tules which in turn invited further deposits. Since that time the river bed in the Needles-Topock stretch has built up at an average rate of 1 1/2 feet a year, thereby causing the low-water surface in the river to rise higher than the bank on each side. This process extended upstream at a rapid rate, gradually obliterating the regular course of the river. A dense jungle-like area 12 mi in length and from 1 1/2 to as much as five miles in width now exists in the vicinity of Needles. Aerial photographs reveal a maze of small channels but no main channel. Vegetation has been the dominant factor. It has served to build up with sediment the central part of the so-called swamp at least four feet higher than the sloughs which exist along the two banks. These sloughs contain clear water that has filtered through from the central part of the swamp, all sediment down to the finest particles being screened out by the close-growing tules. In 1941 when Lake Mead filled to a height requiring release of more water than was regularly being released to meet the demands of water users, a serious inundation took place at Needles and an unsatisfactory sanitary condition developed. Up till the end of 1943, inundations at Needles, even during regular water releases from Lake Mead, became progressively worse. The "Needles Swamp" is a case of channel obliteration, exceeded in magnitude only by that of the White Nile in Africa, where that river becomes lost in the papyrus swamp of the Sudd. As in the latter case, the losses of water in the Needles Swamp by transpiration from plant surfaces and by evaporation from water surfaces are enormous. Present plans contemplate the excavation of an artificial channel the full length of the swamp with discharge capacity sufficient to carry flows appreciably greater than the regular water users' demands, without raising water levels to damaging heights [BUREAU OF RECLAMATION, 1947].

Channel deterioration below retarding basins--In contrast with gate-controlled reservoirs, retarding basins equipped with permanently open outlets convey to the river below the full amount of its load during ordinary stages. During high stages, however, part of the sediment load is deposited on the lands overflowed within the basins. The deposits so made sometimes are scoured out, in part, during ordinary stages. Although this action, in many respects, is favorable towards the maintenance of the river channel, its discharge capacity is destined to shrink in the course of time for lack of flushing out. This is an inevitable consequence of the plan on which a retarding basin operates. In principle, its outlet capacity is designed to discharge only so much water as the channel is capable of carrying without causing overflow, assuming a flood of maximum possible magnitude to fill the basin completely. Owing to this basic assumption, a river channel receiving water from a retarding basin rarely experiences a bank-full discharge. Its general tendency, therefore, is to be lacking in scouring velocities, needed for the removal of tributary sediments. Examples are found downstream from the retarding basins of the Miami Conservancy District, Ohio. Dredging to restore channel capacity has been resorted to. Another example is that of Cherry Creek at Denver, Colorado, below the Kenwood retarding basin, where a marked flattening of the profile has resulted. This case, however, is complicated by artificial channel-shortening plus narrowing, which have been responsible for increases in velocity and have effected retrogression of the bed below the dam.

The Sacramento River case--What doubtless ranks as the most remarkable chapter in the annals of river reconditioning in this country, is the rehabilitation of the Sacramento River, California, after its bed had become clogged with placer mining debris over a period of more than 30 years. Cessation of debris dumping, inaugurated in 1884 has enabled the river channels affected to clear themselves. Their competence and capacity in the matter of transporting the accumulated debris has been nothing short of astounding. About 1890 aggrading of the river bed had raised low-water level on the gage at Sacramento, 10.5 ft and as much as 20 ft in the mouths of the principal tributaries. About 1897 a steady bed lowering was noticed which culminated in 1920 when low water at Sacramento gage again registered 0.0 (mean sea level). Since that time the Sacramento River has resumed its normal functioning. Its main tributaries, however, required ten more years to return to normal.

The next chapter in this river drama is about to unfold itself. Since 1930 the transporting capacity of the main river has been more than equal to evacuating the remaining debris still coming down from points far up in the watershed, attributable probably to overly effective interception of mining debris plus natural bedload in the tributaries. With the completion of Shasta Dam on the main river, retention of additional bed-load materials now is likely to complicate further the situation. Engineering skill is girding itself in this case to the task of combating impending channel deterioration on a scale hitherto untried.

Useful examples of what can be accomplished in the way of desilting water diverted for power or irrigation uses, including the return of the intercepted silt to the rivers, are found above Columbus, Nebraska. Three developments there utilize the waters of the North Platte, Platte, and

Loup Rivers, all notorious sediment carriers with concentrations ranging from 500 ppm during low stages to 20,000 ppm during flood flows. Because adequate works for handling silt were provided the operation costs of these works have been quite low[ANONYMOUS, 1936, BOUGHTON, 1939].

Conclusion--The increasing tempo of surface-water utilization and flood control which are being witnessed in North America, is destined to bring with it widespread problems resulting, directly or indirectly, from stream-channel deterioration. Shrinking channel capacities appear to be next in order as the potential source of a new flood menace. The consequent economic damage will be the greater, the longer the day is deferred to give this situation intelligent consideration. Valuable as are the lessons taught by what happened on the Sacramento River, on the Colorado River, and on the Rio Grande, these lessons are not being heeded sufficiently. Western and mid-western streams are likely to be affected most. Although, possibly, in New England, there is least to fear in this connection, because so many of its streams are small and flow in fairly permanent beds, yet there is good reason to believe that its larger rivers are not immune to retrogression or aggradation.

Broadly viewed, unless this country approaches its surface-water utilization, flood-reduction and sediment-control problems with more foresight, future generations may well find themselves confronted with reservoirs filled with sediment, and below them puny, badly deteriorated stream channels, wholly unfit to resume the task of carrying the water and sediment discharges which, formerly, they were fitted by Nature to carry.

APPENDIX I

In order to dispel any misgivings as regards the propriety of including chemically precipitated matter in the definition of sediment, the following excerpts from Webster's International Dictionary, Second edition, are here quoted. Pertinent statements have been underlined by the writer:

Sediment (Latin sedimentum, a settling, from sedere to sit) (1) the matter which settles to the bottom from a liquid, settlings, lees, dregs; (2) geological material, or a mass of it, deposited as by water; to deposit as sediment.

Sedimentary, (1) of, pertaining to, or containing, sediment, as sedimentary deposits; (2) formed by or from deposits of sediment, as, sedimentary rocks (which see).

Sedimentary rock (geological rock formed of sediment, mechanical, chemical, or organic), especially (1) clastic rocks, as conglomerate, sandstone, and shale, formed of fragments of other rock transported from their sources and deposited in water; (2) rocks formed by precipitation from solution, as rock salt, and gypsum, or from secretions of organisms, as most limestone.

Flocculate, to aggregate into small lumps, said of soils, sediments, etc.

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(Manuscript received June 10, 1948; presented at the New England Meeting, Cambridge, Massachusetts, September 19, 1947; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30 Number 3 June 1949

RECENT DEVELOPMENTS IN WATER SUPPLY FORECASTING FROM PRECIPITATION

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Abstract--The use of precipitation-runoff relations for water supply forecasting has been discussed in numerous papers. This paper describes the details of the techniques developed by the United States Weather Bureau in connection with its program of water-supply forecasting. In addition to its use as a forecasting tool, the method may also be employed for interpolation or extrapolation of stream-flow records, and for the evaluation of water resources. Because the analysis involves a long period of record, time trends in the data must be considered. The downward trend of runoff in the Colorado River Basin as compared to observed precipitation is discussed.

Introduction--The literature of the past several years includes many papers dealing with the subject of precipitation-runoff relations and their use in water supply forecasting [ALTER, 1940; LIGHT and KOHLER, 1943; CLYDE and WORK, 1943; BOARDMAN, 1947; STANLEY and KENNEDY, 1947; and BERNARD, 1949]. The authors of these papers have reached a variety of conclusions concerning the reliability of such relations and their use in forecasting. Several attempts have been made to compare precipitation and snow survey data as a basis for water supply forecasting through the analysis of a single basin. The futility of such attempts has been demonstrated by STANLEY and KENNEDY [1947]. Their Table 4 shows that the coefficient of correlation between precipitation and runoff for random ten-year periods on a given basin may vary from 0.50 to 0.95. Thus, because of the limited period of record generally available for snow surveys, one cannot determine the true reliability of the procedure or make a comparison with precipitation data as a basis for forecasting. As shown by Bernard in a discussion of a paper by CLYDE and WORK [1943], the reliability of a relation increases rapidly as the period of record increases. In addition to the statistical problems arising from the short record periods, these comparisons have not always made most effective use of the data at hand. Moreover, climatic factors and the density of the observational networks vary greatly from one area to the other. Thus, many small basins encompass several precipitation stations and are void of snow courses, while in other cases the reverse is true.

ALTER [1940] demonstrated the feasibility of using precipitation data from relatively low-level stations for forecasting runoff from mountain basins. CLYDE and WORK [1943], and Bernard in his discussion of their paper, emphasized this fact and demonstrated that high correlations can sometimes be found with precipitation stations remote from the basin of interest. LIGHT and KOHLER [1943] described a statistical solution developed in pilot studies conducted by the United States Weather Bureau. Since that time, a more reliable method has been developed and applied to about 120 basins representative of nearly all climatic and hydrologic characteristics found in the western states. In addition, exploratory studies have been completed for typical basins in New England. The method now in use has demonstrated consistently high correlation (see Fig. 1), and forecast bulletins covering much of the western area are being issued.

The technique has been simplified and standardized so that clerks can perform much of the development work. In addition to the advantage of low cost in development and operation, the method has shown its flexibility as a tool for issuing forecasts early in the season. The latter feature is important, since much of the advantage of the forecasts to operations planning is lost if they are delayed until late in the year [CRIDDLE and discussion by WORK 1947]. The procedure used is based on a statistical analysis of precipitation and stream-flow data, but adheres carefully to pertinent hydrologic aspects. The Green River near Linwood, Utah, is used as an example in this paper (see Fig. 2).

Preparation of data--LIGHT and KOHLER [1943] described the adjustment of precipitation data to correct for changes in station location or exposure by use of double-mass curves. This adjustment is important if best results are to be obtained. Figure 3 shows the subareas used in adjusting precipitation throughout the western states. A group of base stations was selected for each area, on the basis of record length and areal distribution, and all stations within the area were adjusted to the most recent years of record by comparison with this base. Short periods of missing records were estimated from adjacent stations on the basis of the relative slopes of the double-mass curves.

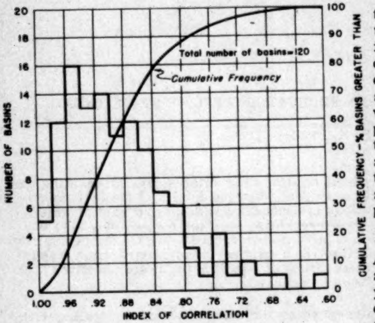

Fig. 1--Frequency distribution of correlation index for precipitation-runoff relations

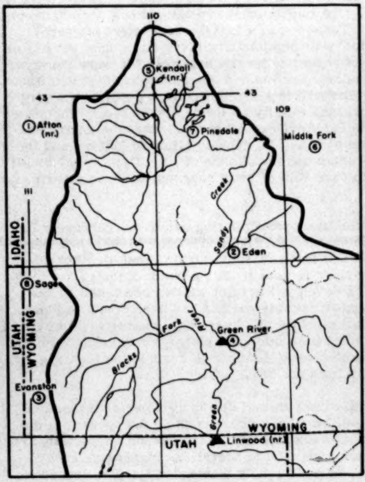

Fig. 2--Green River above Linwood, Utah

It became apparent early in the investigations that stream flow was also subject to time trends and required adjustment. Quite universally in the West, the more recent data show less runoff per unit of precipitation than was observed in earlier years. To eliminate this time trend, the stream-flow data are also adjusted by comparison with a precipitation base. The double-mass curve procedure requires that the relation between the two factors being compared be essentially linear and pass through or near the origin. Since relations between precipitation and stream-flow generally do not meet these requirements, a modified procedure must be used. In the example, the adjustment is accomplished by first plotting observed water-year runoff against the average October-April precipitation at 21 Green River base stations and fitting a curve on the basis of the most recent years of record (see Fig. 4). The Green River discharge records at Linwood, Utah, began in October, 1928. However, a record was maintained upstream at Green River, Wyoming, from 1915 to September, 1939. The records for the two stations were combined so that the total period of record used in the analysis is 31 years.

A double-mass curve (see Fig. 5) is constructed by plotting observed runoff against that computed from Figure 4, and the stream-flow data are adjusted in accord with the relative slopes of the various segments of this double-mass curve. This chart indicates that the early records for the Green River station must be reduced by a factor of 0.81 to make them comparable with the Linwood records, in spite of the fact that the drainage area above Linwood is almost twice as great. In order to determine whether the decrease in slope of the double-mass curve in recent years is the result of a time trend or is caused by the fact that Linwood flows are normally less than those at Green River, Figure 6 was prepared by plotting the runoff of the two stations for the overlapping period of record. This chart shows that while the flows are not proportional to the drainage areas, Linwood runoff is about 20 per cent greater than that of the Green River station.

This preliminary stream-flow adjustment results in more reliable correlations in the steps to follow by removing, in part at least, the relative time trend between precipitation and runoff. Another adjustment is made later in the process after a more accurate index to runoff has been developed.

Determination of station weights--It is to be expected in any correlation between precipitation and runoff that the relative importance of each of several precipitation stations will vary. Since, for the problem at hand, it is necessary to use low- and intermediate-elevation stations as representative of high-elevation snowfall, it is important to weight each station in proportion to its value as an index to stream flow. This is accomplished by multiple correlation of total winter (October-April) precipitation at each of several stations in and near the basin with the adjusted water-year runoff Q from the basin. The resulting regression for the area above Linwood is

$$Q = 0.380 + 0.013P_1 + 0.008P_2 + 0.051P_3 + 0.046P_4 + 0.030P_5 + 0.030P_6 + 0.037P_7 + 0.012P_8 \quad (1)$$

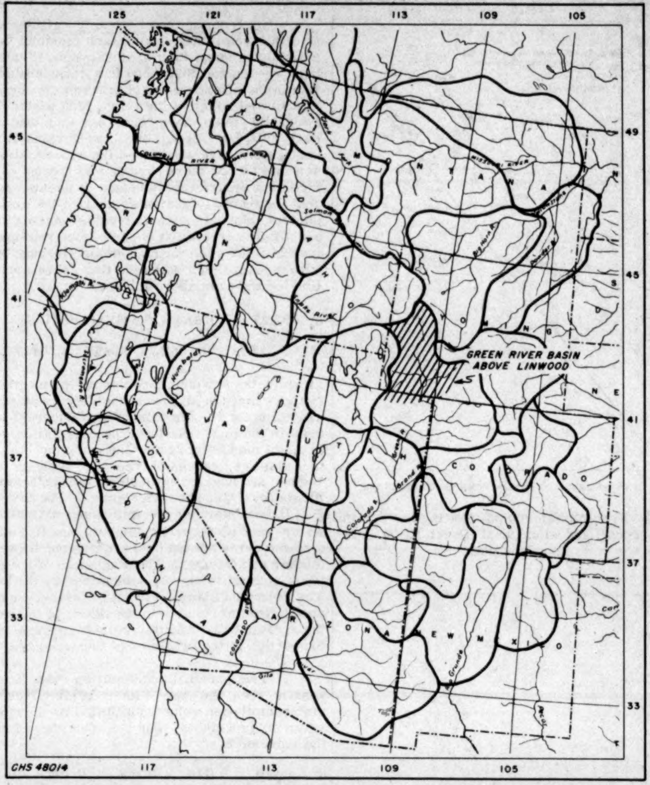
125
121
117
113
109
105
49
45
41
37
33
GREEN RIVER BASIN
ABOVE LINWOOD
WASHINGTON
OREGON
CALIFORNIA
NEVADA
IDAHO
MONTANA
WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
Columbia River
Missouri River
Salmon R
Snake River
Humboldt
Colorado R
Green R
Grand R
Gila
Rio Grande
CHS 48014
117
113
109
105

Fig. 3--Subdivision of western states for adjustment of precipitation data

where Q is in million acre-feet, P_n is in inches, and the subscripts designate stations as shown in Figure 2.

The regression coefficients indicate the relative importance of the individual stations and the station weights are made approximately proportional to these coefficients. Precipitation values measured at adjacent stations are intercorrelated and this tends to magnify the variations in the regression coefficients. For the same reason, however, the exact values of the coefficients are not critical. Hence, the computed coefficients are used only as a guide to the order of importance of the stations. Stations receiving small negative regression coefficients are sometimes assigned a low positive weight, while stations with large negative coefficients are dropped from the analysis. The effective basin precipitation E for any month is, then, the sum of precipitation values at the selected stations multiplied by the respective station weights. In the case of the Green River near Linwood, Utah,

$$E = 0.05P_1 + 0.05P_2 + 0.20P_3 + 0.20P_4 + 0.15P_5 + 0.15P_6 + 0.15P_7 + 0.05P_8 \quad . \; . \; . \; . \quad (2)$$

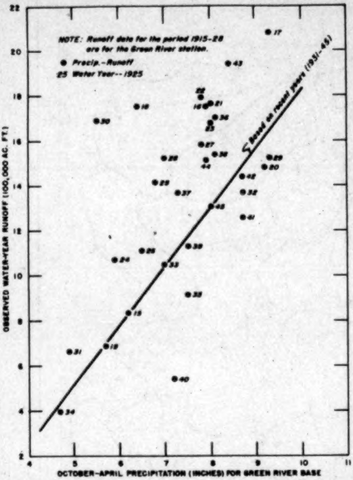

Fig. 4--Precipitation-runoff plotting for preliminary runoff and adjustment (Green River near Linwood, Utah

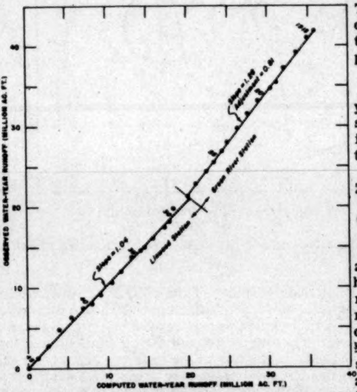

Fig. 5--Double-mass plotting for preliminary runoff adjustment (Green River near Linwood, Utah

Determination of monthly weights--Although precipitation during each month of the year contributes something to streamflow, it has long been recognized that there is a considerable variation in the effectiveness of precipitation occurring at different times of the year. Mid-winter snow generally yields more runoff per inch than does early fall, late spring, or summer rain. Some investigators have subdivided the accumulation season into two or more periods and treated each period as a separate parameter. It seems more logical, however, to assign weights on the basis of shorter intervals such as months. Accordingly, a multiple correlation is performed relating values of E for each month, October through May, with stream flow. The resulting regression equation for the area above Linwood is

$$Q = 0.127 + 0.024E_1 + 0.373E_2 + 0.218E_3 + 0.306E_4$$

$$0.233E_5 + 0.126E_6 + 0.046E_7 + 0.127E_8 \quad ..(3)$$

in which the subscripts designate the months of October through May, successively. Although precipitation for the ten months September-June is used in the final relations, the correlation is based on eight months to reduce the work involved and to increase the degrees of freedom. Weights for September and June are estimated from the trends indicated by (3), as shown in Figure 7. The direct stream flow from September precipitation is not included in the water-year (October-September) runoff, and therefore the curve should be discontinuous between September and October. The magnitude of the break is, of course, in no way determined by the analysis. The computed standard errors of the regression coefficients are shown in the figure to indicate their reliability. Monthly weights are assigned in proportion to the ordinates of the smoothed curve.

The seasonal precipitation index Z for any year is, then, the sum of the monthly effective basin precipitation values multiplied by the respective monthly weights. For the area above Linwood, the equation is

$$Z = 0.04E_0 + 0.09E_1 + 0.15E_2 + 0.19E_3 + 0.19E_4 +$$

$$0.13E_5 + 0.08E_6 + 0.06E_7 + 0.04E_8 + 0.03E_9 \cdot (4)$$

Determination of carry-over effect--An area underlain by deep porous lava deposits may have a ground-water storage capacity capable of maintaining flow, at a diminishing rate, for a period of many years without replenishment by precipitation. At the other extreme, rivers rising in basins having steep, rocky slopes with a shallow soil mantle may have negligible ground-water storage. The geologic structure of the basin controls, in great part, the carry-over from year to year and this effect may vary considerably even in adjacent basins. The magnitude of the carry-over on basins where appreciable sub-surface storage exists depends upon the volume of accumulated storage, which is in turn dependent on the precipitation over a period of years.

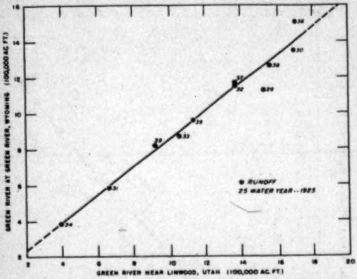

Fig. 6--Water-year runoff relation between the Linwood and Green River stations, based on the concurrent period of record 1929-1939

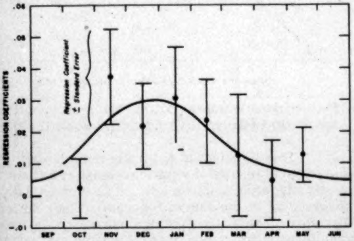

Fig. 7--Determination of monthly weights from smoothed regression coefficients (Green River near Linwood, Utah)

The effect of precipitation in any year upon runoff in the following year is determined by a multiple correlation between runoff and the precipitation indices for the corresponding and next previous years. If the regression coefficient for the previous year is as much as 25 per cent of that for the current year, a second correlation is performed introducing the indices for two or more previous years to determine whether significant carry-over beyond one year exists. Since stream flow in any year integrates the effect of precipitation over several years, the previous year's discharge may be used in lieu of several years of antecedent precipitation in those basins with significant long-term carry-over.

In the case of the Green River, there does not appear to be any significant carry-over beyond one year. Accordingly, the precipitation index for the previous year was assigned a weight of 0.1, corresponding approximately to the ratio of the two regression coefficients.

Thus, the total precipitation index for any year is

$$I_1 = Z_1 + 0.1Z_0 \;.\;.\;.\;.\;.\;.\;. \quad (5)$$

This index I is the only factor used in determining the runoff for any year.

Final runoff adjustment--The preceding steps provide an index which is a far better guide to the annual runoff of a basin than the average precipitation at a group of base stations selected for the precipitation adjustment. Therefore, a final runoff adjustment is determined by plotting values of the index I against corresponding values of observed runoff (see Fig. 8) and fitting a curve to the most recent data. The runoff is then adjusted on the basis of a double-mass curve plotting (see Fig. 9) of observed runoff against runoff computed from the curve of Figure 8. It will be noted that the plotting based on the more accurate index indicates less runoff at the upstream station as shown by the break at 1929, but the other two breaks demonstrate the downward trend in runoff as compared with measured precipitation.

The final relation is determined graphically by plotting the precipitation index against adjusted runoff and drawing a curve of best fit (see Fig. 10). Because of the high correlation a least squares line is not necessary. Moreover, a graphical relation permits the introduction of curvature which has been found necessary for many basins. The adjusted correlation coefficient for the combined record is 0.82. However, using the same regression line, the correlation coefficient for the Linwood record (1929-1945) is 0.93.

Use of relations in forecasting--The relation developed as outlined above permits an estimate of water-year runoff when precipitation from September through June is known. If the relation is to be used for forecasts prior to July 1, an assumption as to precipitation between the forecast date and June 30 must be made. The Weather Bureau has adopted the median index of record as the best estimate of this precipitation. The median value assumed is not the sum of the median monthly values, but is the median of the actual accumulated indices for the period from any forecast date to June 30. This feature makes it possible to issue a forecast as of the first of any month, an advantage not often possible where snow survey data are used because of the lack of adequate data on snowpack water equivalent during the early months of the season. There is, of course, no assurance that the median index will actually occur, but there is equal probability that the observed index will be above or below the median.

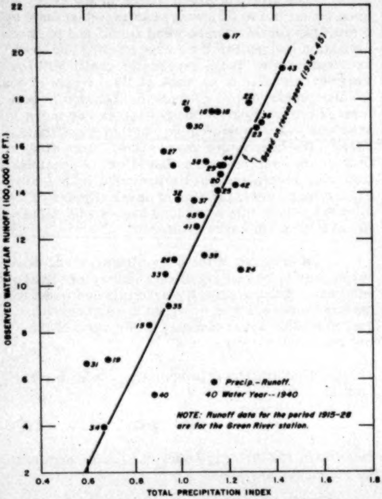

Fig. 8--Precipitation-runoff plotting for final runoff adjustment (Green River near Linwood, Utah)

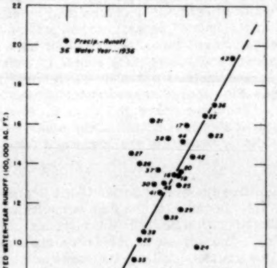

Fig. 10--Final precipitation-runoff relation for the Green River near Linwood, Utah

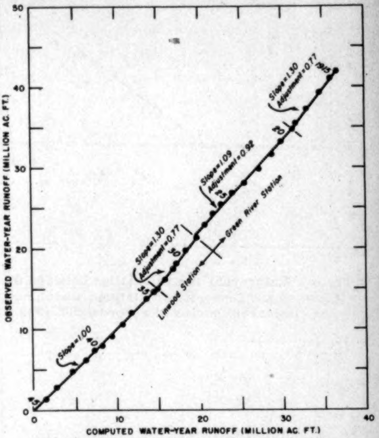

Fig. 9--Double-mass plotting for final runoff adjustment (Green River near Linwood, Utah)

This problem is naturally not unique to this particular type of relation. Most relations of other types now in use are based only on data observed up to the date of forecast. The relation, therefore, inherently assumes normal or average precipitation for the balance of the season. **STANLEY and KENNEDY** [1947] use the standard error of their forecasting relation as a measure of the possible effect of deviations from normal of subsequent precipitation, by expressing the forecast as a range of plus or minus approximately 1.6 standard errors from the mean. The probability is 0.9 that actual flows will fall within this range. The range includes not only the effect of subsequent precipitation, but also the errors of the relation itself and it further assumes that the combined effects are normally distributed about the mean.

Using the relations described above, a forecast can be prepared on the assumption that subsequent precipitation will equal the maximum, minimum, quartiles, or any other specified value in the precipitation record. Thus, it is possible to separate the effect of subsequent precipitation from the other factors affecting forecast accuracy and to provide an estimate with any specified probability of occurrence.

A considerable amount of effort is involved in the preparation of a precipitation-runoff relation. Therefore, since the relation between water-year stream flow at a station or group of stations in the headwaters and at some downstream point is usually

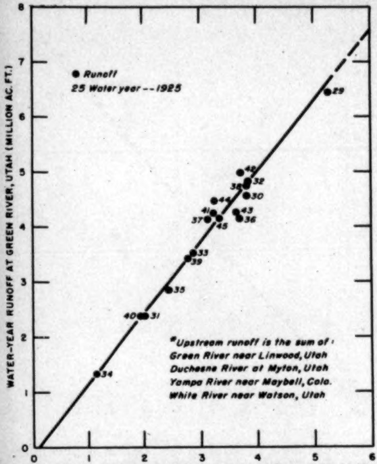

Fig. 11--Runoff relation for determining the flow of the Green River at Greenriver, Utah, from the flow at upstreams stations

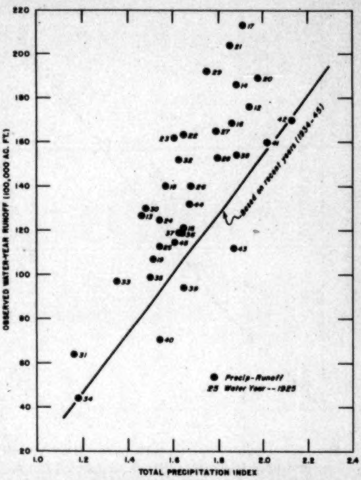

Fig. 12--Precipitation-runoff plotting for final runoff adjustment (Colorado River at Lees Ferry, Arizona)

very good, estimates of flow at downstream stations are based on simple runoff relations such as shown in Figure 11. These relations are based on observed runoff at all stations, giving most consideration to the recent data.

Streamflow normals--Water-supply forecasts are quite frequently expressed in per cent of normal in order that they will be of some value to one not familiar with the variations in flow volume which might be expected at a particular station from year to year. Since the studies indicate definite time trends in runoff, trends which vary in magnitude from basin to basin, it seems appropriate to consider an adjustment in the normals used in the forecast bulletins.

The runoff normals published by the Weather Bureau in their forecast bulletins are based on 1920-1944 data adjusted to conditions existing during recent years. For headwater areas, the normals are determined directly from the adjusted data upon which the precipitation-runoff relation is based. However, a different approach is required for those downstream stations for which no direct precipitation-runoff relation is developed.

In considering precipitation, the assumption is often made that short-period averages for different stations are directly proportional to long-period normals. Somewhat this same technique has been used to determine downstream runoff normals, except that allowance was made for the fact that relations of runoff versus runoff may not pass through the origin. Specifically, the point determined by normal streamflow at all stations was assumed to be along the best straight line passing through the averages of the plotted data (see Fig. 11). Thus, the downstream normal is the value on the line which corresponds to normal upstream flow. This method of routing normal flows downstream is considered to be sufficiently accurate for most purposes, but can lead to cumulative errors if carried too far.

Two other methods of determining downstream normals are immediately apparent: (1) by routing each year's adjusted runoff downstream for the full period upon which the normals are to be based; and (2) by adjusting the flows at downstream points on the basis of a precipitation index for the drainage area above. Both of these methods are more reliable than that actually used, but they also require considerably more computational work.

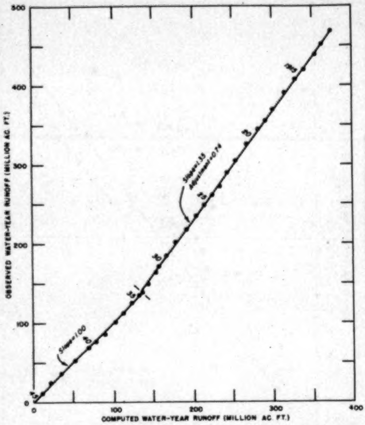

Fig. 13--Double-mass plotting for final runoff adjustment (Colorado River at Lees Ferry, Arizona)

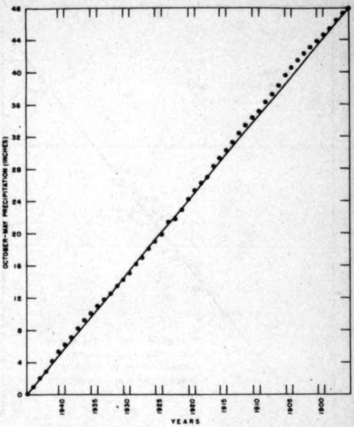

Fig. 14--Mass plotting of October-May precipitation for 21 long-record stations in or near the Colorado River Basin

The effect of estimated normal water-supply on the planned economy of the semi-arid West is of extreme importance. As a result, the normals published in the Weather Bureau forecast bulletins have been the subject of considerable discussion. In view of this fact, an extensive study was made to determine the 1920-1944 average flow for the Colorado River at Lees Ferry, Arizona. The precipitation indices (as developed by the analysis described earlier in the paper) for 16 headwater areas were weighted according to relative streamflow contribution. In this manner, an integrated index, based on 66 precipitation stations, was developed for the entire area above Lees Ferry. The runoff record was then adjusted to the precipitation index in the manner described for the headwater basin (see Fig. 12 and 13).

A third check was made on the Lees Ferry runoff record by adjusting the records for the Green River at Greenriver, Utah, the Colorado River at Cisco, Utah, and the San Juan River at Bluff, Utah, and routing the adjusted normals for these three stations downstream with a direct runoff relation. The average 1920-1944 flow (in millions of acre-feet) at Lees Ferry as computed by the three different methods is: (1) successive routing from headwater areas, 10.5; (2) routing from Green River, Cisco and Bluff, 10.8; and (3) directly from 66 precipitation stations, 11.2. Although the three values were not derived in a strictly independent manner (especially the latter two), it is believed that the analyses are reliable to the extent that the 25-year normal flows at Lees Ferry can be assumed as eleven million acre feet, to the nearest half million.

Causes of time trends in precipitation-runoff relations--The possible causes of the time trend in precipitation-runoff relations which has been noted over much of the West are numerous. To generalize, however, any of the following factors may contribute: (1) a trend between actual and measured precipitation; (2) a downward trend in actual precipitation; (3) a trend between actual and measured runoff; and (4) increased water utilization and evaporation losses. The observed trends are very probably the result of a combination of these factors.

Although it is not inconceivable, it seems highly remote that the precipitation index computed from 66 stations (which were adjusted to four separate bases) should have a significant trend other than one of a climatological nature. Possibly the gradual shift from the ten per cent rule toward the direct weighing of representative snow samples and the installation of windshields could have produced a slight trend between observed and actual precipitation. It is known that the assumed ten per cent water equivalent of snow may be either too large or too small for any particular storm. There is little chance to evaluate this effect, however, since there is no way of deter-

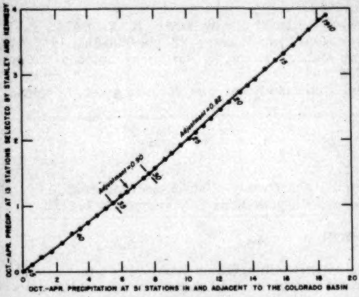

Fig. 15--Double-mass plotting of observed October-April precipitation showing the time trend in the data used by Stanley and Kennedy

mining which of the data were based on the ten per cent rule. Comparative observations indicate that the installation of an Alter shield may increase the catch by ten per cent or more, depending upon local exposure, wind velocity, and other factors. Inasmuch as ten of the 51 stations used in the computation of the Colorado River precipitation bases now have windshields (most of which were installed since 1940), it would seem that this factor is relatively unimportant. A downward trend in precipitation is sometimes advanced as a cause of the trend of the precipitation-runoff relation. An examination of Figure 14, however, shows that the precipitation since the middle thirties has been greater than the 50-year average, based on 21 long-record stations in and near the Colorado Basin.

It is beyond the scope of this paper to analyze the possible causes of a time trend between actual and measured discharge. However, progressive improvements in equipment, measurement techniques, and methods for computing discharges throughout the years have caused a slight trend.

That increased water utilization and reservoir evaporation contribute to a downward trend in runoff as compared to precipitation is amply demonstrated by the data in Table 1. According to these figures, published by the United States Bureau of Census, there were 70 per cent more storage reservoirs in the Colorado Basin in 1940 than in 1930. While evaporation losses may not have increased in direct proportion, an average annual evaporation of five or six feet over the increased reservoir area is undoubtedly an important item. The gradual increase in the acreage irrigated is also supported by the census data.

Table 1--Colorado River irrigation census

Census	Irrigated acreage		Storage dams		Diversion dams	
	Area	Increase since 1920	Number	Increase since 1920	Number	Increase since 1920
	ac	pct		pct		pct
1940	2,638,000	13	840	49	4391	78
1930	2,537,000	9	494	-12	3155	28
1920	2,327,000	. .	565	. .	2468	. .

As a matter of interest, it was noted that the average precipitation at the 13 stations selected by STANLEY and KENNEDY [1947] shows no time trend as compared with the measured Colorado River runoff. The stations were selected because their unadjusted records were better correlated with unadjusted runoff. Figure 15 shows a double-mass plotting of the 13-station average against a group of 51 stations in and near the Colorado Basin (all observed October-April data). With the striking resemblance between this curve and that of Figure 13, it is obvious that no pronounced time trend would show up between the 13-station average and runoff. In other words, the basis of selection used by STANLEY and KENNEDY [1947] favored those precipitation stations which have a time trend corersponding to that of runoff.

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U. S. Weather Bureau,
Washington 25, D. C.

(Manuscript received June 14, 1948; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 21, 1948; open for formal discussion until November 1, 1949.)

DISCUSSION

H. E. Thomas (U. S. Geological Survey, Salt Lake City, Utah)--This paper shows that considerable progress is being made in correction for factors which have heretofore produced inaccuracies in forecasting stream flow. Several of the factors mentioned have appeared to influence runoff in small drainage basins on the west slope of the Wasatch Range, as shown in a recent study [THOMAS, H. E., and NELSON, W. B., Ground water in the East Shore area, Utah, pt. 1, Bountiful district, Davis County; Utah State Engineer Tech. Pub. 5, pp. 127-131, 1948] in which the discharges of Centerville and Parrish Creeks, near Centerville, Utah, were compared with precipitation at representative stations used to forecast the stream flow of adjacent drainage basins. Ordinarily about 60 per cent of the annual precipitation in this area occurs in the six months from October to March. In the ten-year period of concurrent records, the weighted October-March precipitation at four stations could have been used as a basis for forecasting the annual flow of the streams within ten per cent of actual in six years, and within 25 per cent of the measured flow in three additional years. In three years, exceptional precipitation in April and May was evidently responsible for part of the difference between computed and measured runoff. On the other hand, there was close correlation between October-March precipitation and yearly runoff even in years when summer precipitation was exceptionally heavy, and it is inferred that summer precipitation makes a negligible contribution to runoff.

The correlation between rainfall and runoff was poorest in 1942, the year of highest runoff in the period of record. In that year the runoff was about 30 per cent greater than would have been expected from the precipitation. The heaviest precipitation during the ten-year period occurred in 1941, and it is likely that water amounting to about one-quarter of the average annual discharge of the streams was stored in the ground and was not released until 1942. This ground-water stored evidently does not comprise a uniform proportion of the precipitation, for in most years there is a good correlation between precipitation and runoff in the same year.

Changes in ground-water storage may also be responsible in part for the change in the precipitation-runoff relationship since 1935, observed by Kohler in the Green River, and noted in many other western streams. Storage in ground-water basins throughout Utah was at an all-time minimum in 1935, and there has been a marked increase in storage in nearly all basins since that year. Increased ground-water storage would doubtless result in decreased runoff per unit of rainfall. The accuracy of forecasting might be increased if these changes in ground-water storage were evaluated by means of observation wells in the drainage basins, and the forecasts modified accordingly.

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

RESERVOIR SYSTEMS IN MAINE

Miner R. Stackpole

The numerous lakes and ponds that are found in almost every portion of the State of Maine are important resources of the state. There are 2222 bodies of fresh water that are classed as great ponds, that is, ponds whose areas are ten acres or more, and the total area of these lakes and ponds is about 1500 sq mi. These are a result of glaciation of the region. Some of these ponds are very deep: depths of 100 ft have been found in many lakes. In Moosehead Lake there are places where the water is 250 ft deep and in Sebago Lake as much as 315 ft. The deepest part of Sebago is 45 ft below mean sea level.

The topography of the state is such as to make water storage on a large scale feasible at many points. One important feature is that many of the large lakes are near the heads of the rivers and the high elevation of the headwater lakes is a matter of great importance in connection with water power. Practically all of the large storage reservoirs in the state were created by building dams at lake outlets and raising the natural levels of existing lakes. Starting at the eastern boundary of the State the five major reservoir systems are listed in Table 1.

Table 1--Reservoir systems in Maine

River	Area of controlled water surface	Total usable storage	Depth of storage on drainage area	Controlled drainage area	Total drainage area
	sq mi	million ft^3	in	sq mi	sq mi
St. Croix	127	25,000	8.2	1320	1470
Penobscot	102	55,000	12.4	1910	7760
Kennebec	137	31,800	11.0	1240	5550
Androscoggin	88	28,100	11.6	1045	3430
Presumpscot	64	12,000	11.9	436	615

It may be seen that most of the larger reservoir systems in the headwater areas of Maine have usable storage space for from eight to 12 inches of runoff, which amounts to almost one-half the average annual yield.

All of these reservoir systems are controlled by private companies that operate plants on the rivers. The operations are generally satisfactory, with a minimum of complaints from other interests. Most of the complaints came from parties concerned with recreational activities. Practically all of the reservoirs can be classed as multi-purpose reservoirs. Although they are operated primarily for power and log-driving, they also serve to reduce floods and to dilute pollution, as well as to provide many recreational facilities. As minimum flow in streams in northern Maine usually occurs in the late winter, just before the spring runoff begins, these reservoir systems are protection not only against droughts in summer but winter droughts as well. In winter, precipitation in the interior of Maine is largely snow which makes almost no contribution to stream flow until it melts in the spring. At the time of maximum accumulation, usually about the last of March or the first of April, the usual water equivalent of the snow in the interior of the State is approximately eight inches. As most of the larger reservoir systems hold more than eight inches of runoff, the normal spring rains also serve to fill the reservoirs. A knowledge of the water equivalent of the snow on the ground as each winter progresses is of much value to the parties who control the release of water from the reservoirs so that the rate of storage depletion may be adjusted in accordance with the increase in water equivalent of the snow cover in order to provide storage space for this potential runoff and the runoff from the expected spring rains.

Although the storage reservoirs in Maine were created primarily for power and log-driving, they are also of value in connection with flood control. They cannot be relied upon for flood protection with absolute certainty because a power reservoir is not efficiently operated unless it is refilled at every opportunity, whereas a flood-control reservoir is not properly operated unless its flood storage is kept empty as much of the time as possible. However, experience indicates that most power reservoirs in Maine are not full much more than about two months in an average year. This depends, of course, on the capacity and the tributary drainage area. There is always a probability that there will be some capacity in power reservoirs to retard the peak flow from the area partially controlled. Reservoirs in Maine are usually well down by the first of October and usually nearly empty about the time the spring runoff starts at the end of March. There are records to show that each time there has been a large freshet on the major rivers of Maine the peak flow of the river below the reservoirs has been reduced materially because of them. This protection comes without any cost to the State.

The water stored in the reservoir systems in Maine increases greatly the primary power capacity of the various generating stations. Without storage there would be very little hydropower generated during certain periods each year, especially during the late winter and near the end of the summer. The natural flow during these periods sometimes falls as low as 0.10 cubic foot per second per square mile. However, with the storage now available the flow from the controlled areas seldom falls below one cubic foot per second per square mile, except when water is not needed downstream and is being stored. Table 2 shows the total developed head and installed water wheel capacity on each of the five rivers covered by this discussion.

Table 2--Head and water wheel capacity on five Maine rivers

River	Developed head	Installed water wheel capacity
	ft	hp
St. Croix	140	31,750
Penobscot	340	147,800
Kennebec	365	183,700
Androscoggin	775	224,400
Presumpscot	250	22,100

U. S. Geological Survey,
Augusta, Maine

(Manuscript received June 10, 1948; presented at the New England Meeting, Cambridge, Massachusetts, September 19, 1947; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

REPORT OF THE COMMITTEE ON CLIMATOLOGY, 1947-1948

C. W. Thornthwaite, Chairman

Erwin R. Biel Woodrow C. Jacobs John B. Leighly
Phil E. Church Helmut Landsberg Katherine Hafstad

President Byers reconstituted the Committee on Climatology in the autumn of 1947 with the above membership. No formal meetings could be held because the members were so widely scattered, but suggestions were obtained by correspondence on the proper function of the Committee. Certain concrete research projects were proposed, as well as suggestions of a more general nature. It was agreed that the Committee should undertake to summarize, insofar as its limited facilities permitted, the progress of climatology in the United States during the year. This first report is admittedly incomplete. Comments of the members of the Committee follow.

Helmut Landsberg--My personal suggestion for work for the Committee would be to collect from the individual members suggestions regarding the type of climatological information that will be needed for many practical purposes. It seems to me that we ought to stimulate the operating agencies in collecting the type of material that will become more and more necessary for many practical purposes. I am thinking of radiation records, records of soil temperatures, and similar data, which are not at the moment regularly collected by the majority of climatological stations, and in many of the cases we have just to interpolate or extrapolate in order to get some ideas on these items. In many cases we can only make guesses at the conditions and are consequently unable to answer a great many practical questions that are placed before us. The drawing up of a plan along this line and suggesting it to the United States Weather Bureau, possibly stimulating the Congress to set aside the necessary funds for such things, would seem to me to be eminently worthwhile and helpful if not to our generation of climatologists at least to the next one.

Phil E. Church--Because of the rapid advances in the atomic energy program directed toward those phases which will produce power, and because in the production of this power, contaminants will be discharged into the air, and because of the great likelihood that atomic power units will be located near or in cities, it is my suggestion that the Committee stress the necessity for making climatological studies of the larger cities; such studies to include those elements which affect the dilution or lack of dilution of contaminants, the probable horizontal distribution at the surface where such contaminants may come to the ground and the lower layers, and further, that the Committee be prepared to advise the most suitable locations for the establishment of any atomic power unit in the various cities where such study may be made.

Erwin R. Biel--The most urgent need at the present time seems to me the development of microclimatology. I have just finished a 45-hour graduate course in microclimatology here at Rutgers based primarily on Geiger's new book. It was a real intellectual treat to follow Geiger's reasoning. In spite of its volume certain chapters are rather sketchy and I used plenty of additional material. The interest on the part of agronomists, ecologists, entomologists, soil experts, and other scientists is tremendous. I am sure that in the next few years all kinds of projects will be set up and there is a great danger that without expert advice these scattered efforts will result in duplication, confusion, the use of noncomparable methods, and other uncertainties.

John B. Leighly--I have an idea for a job that seems to me appropriate for the Committee. It is an investigation of fluctuations in climate in North America during the period of instrumental observations. We now have a century or nearly a century, over a good deal of the continent, and that is long enough to find out what has been happening since the middle of the nineteenth century... What I am thinking of is a planned series of studies that would cover both temperature and precipitation at a considerable number of stations in North America, chosen for their long records and for their representativeness of considerable areas. After selecting stations and the elements to be investigated (summer temperature, winter temperature, summer precipitation, winter precipitation, for example), we should decide on some appropriate method of smoothing the curves, and apply it consistently. What would need to be discussed here is whether the smoothing should be done by means of running means or, say, by Fisher's orthogonal polynomials... The important thing would be to use a uniform procedure, so that the data derived could be compared over a large area.

When the material is worked up we should want to compare what trends were found with some function that at least gives an indication of the changes in the circulation of the atmosphere in the northern hemisphere that have taken place while various factors of climate have been changing in the past century... Perhaps we could find a series of individual stations in different latitudes, for which pressures are available for a long period, and use differences in pressure among these stations that show a high correlation with the zonal indices already computed, so that we could extrapolate the zonal index back farther than the maps permit. Of course, the zonal index is only a rough approximation of the properties of the atmospheric circulation, but it is the only one the synoptic meteorologists have worked out thus far. They have shown its relation to some of the important things in current weather, and it would be something on which we could hang our results.

I have been working on what started as a simple job of finding out what the rainiest month is in various parts of California. I have found that there is a significant regional difference, both in latitude and between the coast and the interior, but what turned out to be more interesting is that the time of the peak of the rainy season has not been constant during the period of record. Means computed for the past 40 years show February the rainiest month over a large part of the State, but it is the last 20 years or so that makes that distribution. If one computes means ending 20 years ago one finds January the rainiest. And means ending back in the nineties show December the rainiest month over a good deal of the State. I have used 20-year running means to smooth the curves, and get a pretty close parallelism among most of the stations I have thus far worked with. I haven't finished the job yet, so that I do not know all the regional differences. The curves for the several months do not run at all parallel.

John B. Leighly--I can hardly imagine a discussion of the definition of climatology that would not take into account the historical accidents that have determined the ideas that are associated with the term "climate." I think I know approximately how those ideas have developed in the past 150 years, and should be glad to include a discussion of that development in my contribution. (This discussion grew into an article entitled "Climatology since the year 1800" which will be published subsequently in these Transactions.) In addition to the historial discussion we ought also to have a rather searching inquiry, on logical and practical grounds, of the contributions that the study of climate can make today.

Phil E. Church--I am interested in the changes of climatological characteristics produced by mountains as my main field and also in microclimatology. Both of these fields have had their surfaces scratched only in a few places.

C. W. Thornthwaite--My own primary interest continues to be with the measurement of evaporation from natural surfaces. Since the publication of Thornthwaite and Holzman, "Measurement of evaporation from land and water surfaces" in 1942 [U. S. D. A. Tech. Bull. 817], we have come to realize that success in using the vapor transport method to measure evaporation must await improved instruments for measuring the temperature, wind, and atmospheric moisture and requires revision of turbulence theory. While work is continuing on the improvement of instruments and theory I have sought means of obtaining an approximate empirical answer. In 1946 an evapotranspirometer of my design which I described in these Transactions [V. 27, pp. 721-723, 1946] was put into operation near Mexico City. In 1947 a battery of four evapotranspirometers was established in Toronto, Ontario and another in Seabrook, New Jersey. In 1948 a battery of two began operation in Kapuskasing, Ontario and the number in Seabrook was increased to six. The evapotranspirometer does not provide the elegant solution to the problem of measuring evaporation that the vapor transport method does, but it is an instrument that is relatively inexpensive and that can be operated by usual experiment station personnel, and I am in hopes that installations will be made in various parts of the world. Wide interest has been aroused in the method, and plans have been formulated to establish stations in Argentina, Israel, Saskatchewan, and on the lower Mackenzie river in the Northwest Territory of Canada. I would like to see several stations established in the United States. To obtain a first approximation of the magnitude of evapotranspiration in the United States, I brought together as many observations as I could find on evaporation and transpiration from land areas in the United States (principally irrigation projects in the West and watersheds in the East) and have produced a provisional equation for determining potential evapotranspiration from standard climatological observations. Through use of this formula, I produced a detailed map of potential evapotranspiration in the United States [Geogr. Rev., v. 38, pp. 55-94, 1948]. Much more work remains to be done on this problem and I urge a concerted attack.

Definitions of climatology--The Weather Bureau requested various of its professional staff to formulate a definition of climatology. Thirty-five definitions were submitted; many of them were similar. They divide naturally into three classes; (A) in which climatology is described as the statistical manipulation of weather data, or statistical meteorology, (B) in which the geographical distribution of the climatological factors and their relation to other geographical phenomena are emphasized, and (C) in which climatology is defined as the effect of weather on human activity. Some of the more noteworthy definitions follow:

A (1) Climatology is statistical meteorology.

(2) Climatology deals with the statistics of weather phenomena. It primarily makes use of the frequency of occurrence of specific values of weather phenomena.

(3) Climatology: The summation and analysis, over a period of time, of the daily variation of weather phenomena.

(4) Climatology is that branch of Earth science dealing with the compilation, summarization, analysis, and interpretation of meteorological data.

(5) Meteorology and climatology are closely related in that they both deal with atmospheric phenomena which go to make up weather. A distinction may be that in meteorology one measure of each element is sufficient to describe the weather, whereas climatology is concerned primarily with average, not actual, weather conditions.

(6) Climatology: The study of climate. The climate of a region or location is composed of the summation of the meteorological phenomena which occur in that area producing the characteristic weather of the region or location. Climatology, therefore, is a study of meteorological phenomena, which have occurred, their summations, characteristics, frequencies, extremes, causes, and applications.

(7) Climatology is meteorology minus the pure physics of an atmosphere. As such it may be subdivided into statistical climatology, theoretical climatology, dynamic climatology, synoptic climatology, descriptive climatology, applied climatology (further subdivided, for example, into agro-, industrial-, aeronautical-, marine-climatology) and no doubt others.

B (1) Climatology is the evaluation and interpretation of the various meteorological measurements taken at a given point or in a selected area over a period of time.

(2) Climatology is the study of weather which is typical of a particular place (or area) and time of year (season). It takes account of both the average and the abnormal features of weather, and if it is to be a science, must concern itself not only with description and summarization but also seek causality.

(3) The science which seeks to study and describe the climate of a region or area; as determined from a study of past records at that place, or past records at nearby or similar places; to compare climatic features between different areas or places, or at various seasons or months at the same place, or at different altitudes; and to determine from past records, the probability of climatic occurrences in the future.

(4) Climatology: A branch of meteorology treating with the various weather elements such as temperature, pressure, humidity, and precipitation, applied generally to large areas. In climatology the mean or average value of these weather elements over a period such as a month, season, or year are considered. The value of climatology is realized in that these mean weather elements dictate the way in which one lives.

(5) Climatology is that branch of science which deals with the totality of meteorological elements; their magnitudes, variability, distribution, combinations, interactions, and integrated values and effects with respect to space and time. In particular the empirical study and description of this totality as determined from the historical record of observations.

C (1) Climatology is that branch of meteorology which deals with applications of weather information to various human activities.

(2) Climatology is the science of relationships between weather and man in his life on the Earth and in the atmosphere.

(3) Climatology is the study of the effects of weather elements for an operation or class of operations. These effects are usually expressed in terms of the chances of occurrence of the weather elements, based on definite operational limits.

(4) Climatology is the treatment of all types of weather data and the application of them to all fields of human endeavor, and to prognostic and experimental research in weather problems.

Through discussion with members of the Committee it was brought out that the more important divisions of climatology needing investigation at the present time are physical climatology, paleoclimatology, microclimatology, industrial climatology, bioclimatology, agricultural climatology, medical climatology, military climatology, and statistical methods in climatology. There is considerable overlapping among these subdivisions but they indicate that the content of climatology goes far beyond mere statistical meteorology.

Microclimatology--At the present time, work is progressing actively in the field of microclimatology. Microclimatology deals with the areal and vertical distribution of properties of the layer of air near the ground and is to be distinguished from micrometeorology in objective and in type of analysis. Micrometeorology is concerned with the physics of the layer and aims at discovering physical principles, whereas microclimatology deals with the geographical distribution both areally and vertically of the climatological elements under investigation and seeks patterns of geographical distribution. The various projects dealing with the layer near the ground are concerned with both microclimatology and micrometeorology. On March 18 and 19, 1948 a symposium on micrometeorology was held under the sponsorship of the Electrical Engineering Research Laboratory of the University of Texas. A brief summary of the symposium was published on April 1, 1948 as Memorandum No. 7. It described work being carried on in various parts of the country, including that at the Daniel Guggenheim Airship Institute, the Department of Engineering at the University of California at Los Angeles, Brookhaven National Laboratory, Argonne National Laboratory, the Army Chemical Center, Cook Research Laboratories, the Department of Meteorology at the University of Chicago, and the Department of Electrical Engineering of the University of Texas. The symposium was the idea of Earl Droessler, meteorologist with the Office of Naval Research.

In addition to the work on microclimatology presented in the symposium, the University of Maryland has for more than a year been conducting a library survey of world literature and data of microclimatology under the sponsorship of the Office of the Quartermaster. Bibliographies have been published and reports prepared which give means for reducing records of temperature and wind from the level of observation to the level of a standing man.

The Johns Hopkins University Laboratory of Climatology has inaugurated a detailed study of microclimatology at Seabrook, New Jersey under the joint sponsorship of the United States Air Forces and the Seabrook Farms Company. It is recognized that the primary need is for detailed simultaneous and accurate measurements of the properties of the air near the ground. These include (1) temperature and temperature gradients, (2) wind gradient and wind shear, (3) humidity and humidity gradients, (4) evaporation and transpiration, (5) radiation and insolation, and (6) turbulence. To obtain observations of the required accuracy new and improved instruments are indispensable. Instrumentation remains the basic problem of the investigation. At the same time, it is recognized that the compilation and evaluation of data must keep pace with its collection. It has been recognized that an integrating instrument that would measure various values simultaneously would possess many advantages. Work has been conducted on the design of an instrument for the combined measurement of temperature, humdity, and wind velocity in which all three parameters will be expressed as temperatures.

Instruction in climatology--No systematic survey of courses of instruction in climatology was possible. In response to requests from various members of the Committee the following information was received.

Phil E. Church--The University of Washington established the Department of Meteorology and Climatology in mid-1947. A number of courses in climatology was subsequently approved by the University Curriculum Committee. These courses have the following titles and credits.

Meteorol. 121 Physical Climatology	5 quarter credits
Meteorol. 122 Regional Climatology	5 quarter credits
Meteorol. 128 Applied Climatology	5 quarter credits
Meteorol. 129 Microclimatology	3 quarter credits
Meteorol. 192 Readings in Climatology	to be arranged
Meteorol. 193 Special problems	to be arranged
Meteorol. 195 Climatological statistics	to be arranged
Meteorol. 200 Seminar	to be arranged
Meteorol. 300 Research	to be arranged

Needless to say, the above list is for upper division students; we have an introductory survey course, and we are offering a course on Weather Observation which is to acquaint students with the technique of taking observations at a model weather station and also in the field.

Erwin R. Biel--We offer here at Rutgers University in the Department of Meteorology, three full semester courses for undergraduates, three full semester courses for graduates, and one graduate research course for students working toward a Master's Degree.

Undergraduate courses	
1 Elements of Meteorology	3 credits
2 Elements of Climatology	3 credits
3 Climates of the United States	2 credits

	Graduate courses	
1	Microclimatology	3 credits
2	Advanced meteorology	3 credits
3	Advanced climatology	6 credits

In the undergraduate courses the emphasis is on physical principles underlying climatic phenomena with a minimum of regional details. In the graduate courses practical applications are stressed (agricultural climatology, medical climatology, frost protection, shelter belts, forest, cities). They also include a detailed coverage of regional climates including oceans.

John B. Leighly--Instruction in climatology here at the University of California is where it always has been. Last year I tried a seminar on " applied climatology" but it was a failure. The students did not have enough background to read critically the literature on the subject. I still think that graduate work in climatology should be built on a thorough undergraduate training in meteorology, and that only institutions that can offer such training should undertake graduate work.

C. W. Thornthwaite--Graduate work in climatology was initiated at the Johns Hopkins University in the fall semester of 1947. Instruction in climatology will develop slowly. We recognize the necessity of a solid foundation in meteorology but we do not intend to offer it ourselves. Instead, we will select students who already have the background. Students not having it who want to specialize in climatology will be expected to get meteorology in one of the going departments of meteorology elsewhere. Furthermore, a thorough foundation of mathematics, physics, statistics, and biology is required. Formal courses in climatology are few. At present they include the following:

Dynamic meteorology
Physical climatology
Statistical methods in climatology
Regional climatology
Microclimatology
Physiological climatology
Soils and land use in humid equatorial regions
Summer field course

We consider the most useful part of the training in climatology to be the summer field course. It is given at the Laboratory of Climatology at Seabrook, New Jersey. Students working in the Laboratory receive board and room and a salary. There are no examinations or grades and there is no tuition. The practical problems in climatology at Seabrook Farms are many and varied. In addition, the work in microclimatology which the Laboratory is performing for the Air Forces gives added opportunity for wide student training. We do not intend to accept more than a few students; thus it will be possible to select them very carefully.

Johns Hopkins University Laboratory of Climatology,
Seabrook, New Jersey

(Communicated manuscript received January 28, 1949;
open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

REPORT OF COMMITTEE ON SNOW, 1947-1948

R. C. Farrow, Chairman

An epic--James Church, tireless and apparently ageless, returned in the late spring of 1948 after establishing snow-survey systems in the Himalaya and the Andes throughout 1947. During March, April, and May 1947 he traveled over 300 mi on horseback mostly on Himalaya Yak trails, starting snow surveys at 17,000 ft elevation. By June he was in New Delhi producing a book-size report.

August 1947 found him in Argentina planning snow surveys for the Government. By September he had flown the Andes from end to end, his pilot claiming it to be the first such flight on record.

Snow surveys and cooperation

Snow surveying by helicopter--The Chairman has felt that this type of flying machine held the solution to the snow surveyor's travel problem. The United States Geological Survey has taken the initiative by using one (March 1947) to reach remote snow courses in the Skagit and Cedar River Basins, in Washington. The experiment is described by H. G. Riggs, in The Snow Surveyor's Forum 1948 published by the Western Snow Conference.

Snow Leaders' Conference--This Conference was held at Logan, Utah December 2-5, 1946 under the Chairmanship of Geo. D. Clyde, to discuss common problems in the Northwestern Cooperative Snow Survey Area, comprising British Columbia, Washington, Idaho, Montana, Colorado, Utah, and Oregon. Three matters of importance to snow surveys and forecasting resulted from the meeting.

(1) It was submitted that from ten to 15 samples gave as good results as 30 to 40. A number of courses in British Columbia had been so reduced. It was decided to reduce long courses in all areas.

(2) Also of importance to forecasting was standardization of the period of record to be used for normals, in order that all snow survey reports and forecasts might be issued on the same basis.

(3) Finally, a standard presentation of snow survey reports, and supporting data was worked out and agreed upon. It was felt that this would be of value to those who receive and use a number of different reports.

Snow surveys in British Columbia were expanded during 1946 and 1947, after marking time during the war years. Eighteen new snow courses were laid out, four in the coastal area, 14 on Columbia River Drainage, which will materially assist the International Columbia Basin Cooperative Forecasts; more will be laid out this year.

A record snow sampling appears to have been made on the Loch Lomand Course in British Columbia, March 30, 1946, elevation 3800 ft, depth of snow 305 inches, water equivalent 146 inches.

Experimental air surveys are being undertaken in British Columbia to map snow-covered areas and elevation of snow line at two-week intervals to try and correlate with snow surveys and subsequent runoff.

A new departure in snow surveys reported by R. A. Work (Soil Conservation Service, Medford, Oregon)--An interesting and perhaps significant departure from traditional snow-survey methods will be initiated in the Montana snow-survey field in 1948. To serve a need of the United States Bureau of Reclamation for more detailed information on snow cover at the headwaters of the Missouri River, the Soil Conservation Service, the Bureau of Reclamation, and the United States Forest Service have established a network of 26 snow courses, extending nearly three hundred mi from south to north along the east slope of Montana's Continental Divide.

Departing from the traditional system of measuring a network by several parties of two men or more, traveling by ski, this network will be measured by only two trained Forest Service employees, who will travel together swiftly by means of a Tucker Sno-Cat. The Sno-Cat will be transported through the flat lands on a four-wheel drive high clearance truck. It is believed this procedure will produce uniformly accurate snow surveys and will eliminate the expense that would otherwise be required to provide numerous snow-survey shelter cabins and numerous snow-survey sampling sets for many men traveling by ski or snowshoe.

Snow conferences--The Eastern Snow Conference which held a winter meeting February 6 and 7, 1948 at Pittsfield, Massachusetts is becoming well established. I was invited to attend but distance prevented, and I had to decline reluctantly.

The Western Snow Conference had a most successful meeting, jointly with the Columbia River Basin Water Forecast Committee, and the Northwest Hydrology Section of the AGU at Portland, Oregon, April 21 and 22, 1947. All meetings were well attended and interest was keen.

The Snow Surveyor's Forum came in for favorable comment, its first issue having appeared since the previous meeting. Designed for the field men who do the work, it invites letters, suggestions, and anecdotes from them, and also contains articles and notes of a practical nature by snow-survey leaders. It has been a morale booster and has been well received.

J. Kittredge (University of California, Berkeley, California)--The data collected during several winters on the Stanislaus National Forest on the accumulation, evaporation, and melting of snow under different conditions of forest cover, are being subjected to further analysis since the interruption during the War. A comparison of averages from randomly distributed stations with those from mechanically spaced stations in the same areas of forest indicate that the differences are not statistically significant, so that all seven years of record under the ten different conditions of cover can be used for analysis. The volume entitled Forest Influences has been published by McGraw-Hill Book Co. which contains a chapter on snow and the relation of different conditions of forest cover to the interception, accumulation, evaporation, and melting of snow.

Forrest L. Rhodes (Cooperative Snow Investigations, Oakland, California)--The Cooperative Snow Investigations being conducted jointly by the Corps of Engineers and the Weather Bureau, with the United States Geological Survey, the Bureau of Reclamation, and the Forest Service cooperating to a limited degree, are carrying out much needed basic research at their three mountain snow laboratories. Already they have added importantly to our knowledge of the physics of snow.

In recognition of the influence of snow on the planning, design, and operation of flood control and multiple purpose projects in the mountainous portions of the United States there was initiated in 1945 by the Weather Bureau and the Corps of Engineers, on a cooperative basis, a comprehensive snow-investigation program to:

(1) Determine a practicable and reliable method of evaluating the maximum stream flow which may be produced on a stream by snow-melt, or by combined snow-melt and rain.
(2) Develop a practicable and reliable method of forecasting seasonal and short-term stream flow, including floods, resulting from snow-melt or combined snow-melt and storm runoff.
(3) Expand our basic knowledge of the hydrodynamic and thermodynamic characteristics of snow through a program of fundamental scientific research.
(4) Increase our knowledge of meteorological, climatological, and hydrological phenomena as they influence one, two, and three above.

The program consists of three intensively instrumented field laboratory or study drainage basins, located in California, Montana, and Oregon, and a Program Director's office at the South Pacific Division Office, Corps of Engineers, Oakland Army Base, Oakland 14, California.

In these laboratory basins the following elements are observed:

Weather: Insolation, temperature, humidity, wind, and precipation;
Hydrologic: Stream flow, ground water, soil moisture, and temperature;
Snowpack: Cover from aerial photographs, depth, density, water equivalent, classification, thermal quality, and transmission and storage of liquid water.

Observations are routed to the Processing and Analysis Unit in the South Pacific Division Office, where they are processed, indexed, filed, and analyzed, and where technical reports are prepared.

Data are available for study for (1) three years of observation at Central Sierra Snow Laboratory, a four-square-mile drainage basin on Castle Creek, near Donner Summit, California; (2) three years of observation at Upper Columbia Snow Laboratory, a 20-square-mile drainge basin on Skyland

and Bear Creeks, near Glacier Park, Montana; and (3) one year of observation, chiefly hydrologic, at Willamette Basin Snow Laboratory, an 11-square-mile drainage basin on Blue River, about 40 miles east of Eugene, Oregon, near Mackenzie Bridge.

Other basins within the major river basins and adjacent to the laboratory area are being studied, as it is planned to apply the results of the program over a large area to verify or to modify equations and techniques derived from the extensive investigations in the laboratory areas.

Some results of the program are as follows: A relation between stream flow and temperature which accounts for 95 per cent of the variance in flow; evidence of rapid flow of water through the snowpack; experience with sampling techniques in snow measurements and the magnitude of within-course variance; realization of the dominating effects of local exposure on precipitation, snowpack, and snow melt, as well as a conception of the very large range in these elements within small basins (maximum water equivalent twice to four times as great as the concurrent minimum); a means of estimating solar radiation from temperature data. Observations of penetration of solar radiation confirm those of earlier investigators; and observations of the albedo of snow have been considerably lower than are ordinarily reported.

Findings of the program are distributed in technical reports, which are written by the Processing and Analysis Unit or the Technical Supervisor. Seven reports have been completed, four are in review, and two in preparation. Information as to observations and reports can be secured from the Program Director.

Special instruments have been developed, or are in the process of being developed, by the Technical Supervisor, who is located at the Weather Bureau Office in Sacramento, California. The principal instruments developed so far are: electronic snow-moisture meter; a null-point meter for the bridge used for measuring soil moisture; and a thermocouple pyrheliometer for measuring radiation penetration into the snow.

Symbolic of the widening interest in snow, Canada has set up a Sub Committee on Snow and Ice Research under the joint auspices of the Associate Committee on Soil and Snow Mechanics (R. F. Legget, Chairman) and the Associate Committee on Geodesy and Geophysics, (J. T. Wilson, Chairman) National Research Council.

The Sub Committee is divided into groups according to interest including meteorology, hydrology, physics of snow, mechanics of snow (as effecting over-snow travel for army, air force, and northern transport interests), permafrost, avalanche control, snow removal, and glaciology, with the idea that if it develops satisfactorily it can be raised to the status of an Associate Committee of the National Research Council, its groups becoming sub committees, whose chairmen would meet together periodically in order to coordinate research; the committee as a whole meeting perhaps once a year.

The first meeting was held at Ottawa February 14, 1948, under its Chairman, P. D. Baird, Director, Montreal Office, Arctic Institute of North America.

Two members, R. F. Legget and I are also members of the Committee on Snow, AGU, which favors good liaison. Two meetings a year are planned, the NRC paying traveling expenses.

Snow surveys for over-snow

Transport problems--G. J. Klein, of the National Research Council of Canada has developed instruments for determining snow properties in the field, as described in Technical Memorandum No. 5. Standardized methods and instruments for measuring physical characteristics of snow are described. The applications of the measurements are specially designed to define snow conditions from the standpoint of over-snow vehicles. The report includes a snow nomenclature and general information on snow which may be helpful to observers.

Klein's "Nomenclature for Snow" is based on terminology used by Seligman and might well form a basis for a general standard nomenclature. With the widening interest in snow I feel that a standard is long overdue, and propose to have the Committee on Snow work on this.

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Empirical methods of estimating snow-melt rates, Rept. 16, 1948.

APPENDIX I--COMMITTEE ON SNOW

R. C. Farrow, Chairman

Howard T. Barnes
J. E. Church
Phil E. Church
Geo. D. Clyde
R. W. Gerdel
Joseph Kittredge, Jr.
R. F. Legget
Ralph L. Parshall
R. A. Work

Regional Representatives

M. Balls	Quebec
H. P. Boardman	Nevada
E. H. Collins	Washington (coastal)
E. S. Cullings	New York
D. B. Freeman	Nebraska
E. Hinton	Newfoundland
O. H. Hoover	Alberta
J. C. Marr	Idaho
F. H. Paget	California
P. W. Thomas	Maine
Forrest L. Rhodes	Cooperative Snow Investigations

Water Rights Branch,
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(Manuscript received April 15, 1948; and as revised, January 31, 1949; presented at the Twenty-Ninth Annual Meeting, Washington, D. C., April 22, 1948; open for formal discussion until November 1, 1949.)

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

DISCUSSION OF

"SOME ASPECTS OF GEOPHYSICS IN CANADA WITH SPECIAL REFERENCE TO STRUCTURAL RESEARCH IN THE CANADIAN SHIELD (PART 2: AN APPROACH TO THE STRUCTURE OF THE CANADIAN SHIELD)"

by J. TUZO WILSON

Trans., v. 29, pp. 691-726, 1948

J. F. Henderson (Geological Survey of Canada, Ottawa, Canada; published with the approval of the Director, Mines, Forests, and Scientific Services Branch, Department of Mines and Resources)--Wilson has shown some of the uses of air photographs in the geological mapping of the Canadian Shield. The value of air photographs has long been recognized by geologists and more recently by prospectors for prospecting and development work. The modern Canadian geolgist and prospector do not consider themselves properly equipped unless they have with them in the field photographs of the area they are investigating.

Interpretations of the linears seen on photographs are dependent on examination and study on the ground. Many pronounced linears extending for miles may, on field examination, prove to have little, if any, displacement along them whereas inconspicuous linears may mark major faults. Thus, at Yellowknife, detailed mapping indicates that the great shear zones along which most of the gold ore bodies of the camp have formed, lie along a zone of major overthrusting with a displacement of more than a mile. Yet the zone of thrust faulting, possibly because it is early and offset by the West Bay and Akaitcho Faults of the Indin Fault zone, is not expressed on the surface by a marked linear. On the other hand, a large number of conspicuous linears, such as one extending northeast across the Mackay Lake area for more than 40 mi, are found, on ground examination, to have negligible displacement along them.

Many major linears even after examination on the ground are open to several interpretations. Thus, the Snare lineament, regarded by Wilson as marking a great overthrust fault, may equally well mark an unconformity and it has been so regarded by other geologists who have worked in the area and mapped it on the ground. The Great Slave lineament is regarded by Wilson as marking a transcurrent (strike slip) fault. Yet we know that the northern side was downthrown several thousand feet and have no evidence as to the horizontal component of movement. From the information at hand, the dominant movement seems to have been vertical rather than lateral. South of Great Slave Lake the Taltson lineament may mark a high angle thrust fault as Wilson suggests but there is no evidence from field mapping that it is such, apart from a rough parallelism of the lineament with the fold axes in the basin of the Nonacho sediments to the east.

These examples are cited to show the different interpretations that may be placed on linears in areas that have been mapped and where the linears have been studied on the ground as well as on air photographs. Where no field mapping has been done and interpretations are based solely on the study of photographs, they are even more highly speculative. This does not detract from Wilson's paper in any way. Whether or not we agree with his interpretations and conclusions, such a broad and speculative approach is most stimulating and refreshing and a valuable contribution to our study of the Shield. However, let us not assume that the study of air photographs is a ready panacea for solving our structural problems. Air photographs have proved a great aid in our mapping but, as Wilson states in his introduction, "The use of new geophysical methods and of air photographs is assisting mapping but there is no indication yet that any combination of these methods will dispense with the need for slow field examination."

C. S. Lord (Geological Survey of Canada, Ottawa, Canada; published by permission of the Director, Mines, Forests, and Scientific Services Branch, Department of Mines and Resources)--I have read Wilson's paper with interest and I was particularly concerned with his treatment of the Precambrian area of western Northwest Territories where, during the past 12 years, I have mapped geologically, some 11,000 sq mi and have at all times made use of available air photographs before, during, and after the respective field studies.

In such a district, embracing vast unmapped areas interspersed with scattered areas mapped mainly on a scale of one inch to four miles, it is perhaps inevitable that some differences of opinion should arise between investigators; probably, were the whole truth known, each has arrived at some truths, some fallacies. Reconciliation of ideas will doubtless come with time and study; but in the interim we cannot afford to ignore completely basic field data despite their failure, at times, to fit or support enticing and stimulating theories.

The author's inference (p. 709) that the north half of the Ingray Lake map area was mapped without reference to linear topographic features will bear qualification. We were, of course, aware of their usefulness and importance. So also were the geologists of Territories Exploration Co., Ltd. who in 1938 compiled the first geological map fo the Indin Lake area, a map that outlined a number of faults (and linears) of the subsequently named Indin lineament. It was my duty to prepare the manuscript for the Ingray Lake map [LORD and WILSON, 1942]. Wilson suggests (p. 710 and Fig. 24 and 25) that full use was not made of linears in this compilation. Admittedly one may speculate as to the origin of many of these features, and it is possible, even probable, that some of them represent unrecorded faults. Nevertheless, some restraint was, understandably, exercised during compilation, and this was defined in the following passage [LORD, 1942a, p. 42] "Faults have been mapped only where geological features are offset or are inferred to be offset. ...Straight topographic features are common elsewhere in the map areas and some of them may mark other faults." The hypothesis that linears may mark faults was continually tested in the field in so far as time and scale warranted. Many such features are unaccompanied by significant displacement and their indiscriminate emphasis in a publication of the Geological Survey of Canada seemed superfluous; particularly since these features are obvious on the topographic maps and air photographs.

Wilson attaches considerable significance to the Snare lineament (p. 710). This, he postulates, marks a major thrust fault, an essential component, in the northwest, of a pattern of continent-wide mountain building (see Fig. 35). Although he admits that its origin due to major thrusting is questionable, he supports that postulate, by drawing comparison between the Snare and Huron-Mistassini lineaments (p. 715); but despite his tacit assumption that the latter feature marks a major thrust much doubt exists as to the validity of the interpretation, as indicated by M. E. Wilson of the Geological Survey of Canada in a personal communication. Thus mutual support has been drawn from two speculations, a line of reasoning that falls short of constituting proof.

The following notes on the Snare lineament, and its origin, appear warranted inasmuch as they are not wholly in accord with Wilson's presentation (p. 710). The lineament crosses the adjoining Ingray Lake [LORD and WILSON, 1942] and Snare River [LORD, 1942b] map areas. Thus Wilson and his assistants mapped, in 1939 about 35 mi of this feature (in the south half of Ingray Lake map area); and the writer and his assistants, in 1938, 1939, and 1940, about 100 (in the Snare River map area and north half of Ingray Lake map area). The author adequately defined (see Fig. 24 and 25) the course of the lineament in Ingray Lake map area, but failed to do so in the Snare River map area to the south. Presumably in the latter area it trends southwesterly through Basler Lake, thence south along a part of Emile River, and beyond to the head of Marian Lake (see Fig. 27).

Within these map areas, Proterozoic strata of the Snare Group rest unconformably on Archaean rocks of the Yellowknife group. Archaean granitic rocks intrude the Yellowknife strata, whereas Proterozoic granitic intrusions invade rocks of both groups. In the southern, Snare River map area, near the lineament, Snare strata are only gently folded; they are in contact with older, Archaean granitic intrusions but are not known to have been invaded by much Proterozoic granite and, accordingly, are relatively unmetamorphosed. To the north, in the Ingray Lake map area, they have been extensively invaded by the younger granitic rocks, and are intensely metamorphosed and commonly steeply inclined. A band of distinctive dolomite comprises a characteristic member within both the gently flexed, relatively fresh strata and their altered, tightly folded counterparts to the north; it has been traced continuously from one to the other and leaves little doubt as to the correlation of the sediments in the two map areas despite the notable difference in their metamorphism and structure.

In the Ingray Lake map area [LORD and WILSON, 1942] the steeply inclined Snare strata adjoin Yellowknife rocks and granitic rocks of uncertain age. The contact lies in a well-defined linear, a part of the Snare lineament. This contact has not been demonstrated to mark a faulted contact, although the possibility that it may do so was recognized despite the author's statement (p. 710) that the linear was shown only as a contact and unconformity; thus [LORD, 1942a, p. 21] "From Arseno Lake southward for 21 mi to Mattberry Lake, dolomite of the Snare group is separated from granitic rocks to the east of it by a deep, continuous valley. The rocks were not found in contact and the granite is not known to cut the dolomite. The topography suggests that the rocks are separated by a fault. If so, the fault probably extends northward along the steep, westerly facing scarp on the east side of Arseno Lake where some rock is highly schistose."

This contact was not mapped as a fault for several following reasons, which, in the aggregate, although they do not eliminate the possibility or even probablility of some faulting, cast much doubt on the hypothesis that the contact represents a major fault (that is, a fault of some miles displacement).

(1) The unconformable contacts in Snare River map area between Snare and older rocks and the increased inclination of Snare strata from south to north suggested that in the more northerly Ingray Lake map area a steeply inclined unconformable contact was to be expected. Differential erosion along such a contact might result in a fault-like linear.

(2) Near the north end of the linear, nine miles north-northeast of the north end of Arseno Lake, the outcrops just west of the linear contain conglomerate beds [LORD, 1942a, pp. 19-20]. These beds dip steeply west, are members of the Snare group, and could well be interpreted as strata lying a few hundred feet stratigraphically above a steeply inclined unconformable contact.

(3) The contact (and linear) very nearly parallels the trend of the Snare strata. The persistent dolomite band already referred to was traced for 60 mi within the Ingray Lake map area and everywhere lies close to or at the contact. This situation does not suggest that the drift-covered contact marks a major fault.

(4) No dislocation of geological features (such as dykes) along the linear was recognized by my party nor, if memory serves aright, by Wilson's party.

The author shows the course of the Snare lineament in the northern part of the Snare River map area on a much generalized figure (see Fig. 27); presumably it is a less prominent feature in that area. However, as I interpret its course from the figure, unquestionable Snare strata outcrop on both sides of the lineament; on the west side the strata were found lying unconformably on granitic rocks, on the east side unconformably on Yellowknife strata and granitic rocks. Thus the existence of a major fault is again open to question, since the lineament does not appear to separate, as Wilson infers (p. 710), an area characterized exclusively by Yellowknife strata from one characterized exclusively by Snare formations.

In another part of his paper (see Fig. 12) Wilson has interpreted the geology of Aylmer Lake map area from photographs. No new technique is involved; similar studies are general practise by officers of the Geological Survey of Canada when preparing for field work in a new area. Similar useful information was derived from photographs of Aylmer Lake map area last year by my field party before and during field work. Nevertheless, the published map [LORD, 1949], compiled from field observations, shows clearly the limitations of such methods and their total inadequacy as substitutes for ground observation.

The above comments, confined to the district with which I am most familiar, may serve to emphasize the controversial nature of the data on which the paper is based. Nevertheless, I take pleasure in heartily endorsing it as an interesting and worthwhile presentation which, although highly speculative, is adequately and properly qualified as such.

His paper will, I am sure, be read with interest and critique by that host of geologists who, for the past decade or more, have come to regard the use of air photographs as an essential supplement to ground surveys.

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J. Tuzo Wilson (University of Toronto, Toronto, Canada, Author's closure)--My former colleagues and old friends, J. F. Henderson and C. S. Lord have been kind enough to make some interesting comments upon my paper. With their general remarks I agree. We appear to differ only in two matters.

The first concerns the field interpretation of certain features especially major faults like the supposed Snare thrust. Considering the reconnaissance nature of most of the work and the fact that we mapped adjoining areas in different summers without ever visiting one another's areas, the remarkable fact seems to me to be that we agree so well and that along 140 mi of common boundaries between Lord's mapping and mine, the only difference of opinion concerning field work is of the nature of one important lineament. This is unfortunate but quite normal and understandable. For instance, Lord also says he doubts the existence of the Huron-Mistassini thrusts although faults are already shown over the whole or part of the suggested location in four publications of the Geological Survey of Canada.

The second point is on the reliance to be placed upon air photographs. Their use to assist field work has so long been normal practice in Canada that I perhaps did not make this clear enough. My own faith in their value was gained during the four summers in which I used them in the field while on the staff of the Geological Survey of Canada. It is to that and other field experiences with photographs that I owe a belief that they can be used to map some features, but not nearly all, in areas where no field work has been done.

The results are certainly not up to survey mapping standards and may in some cases be misleading. They will not replace the need for field work, but for some purposes they are a great deal better than nothing. Younger faults and glacial features, but not of course, petrology, usually show up very well.

Corrigendum--The following correction is noted in this paper as published: On page 717, the right-hand side of Figure 31 should be at the bottom to conform to the orientation of Figure 30 and 32.

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the *Transactions*:

Vol. 30, April 1949, in the paper by Norman Ricker, p. 185, in the title of Figures 1, 2, and 3, the symbol should be $\mu|_{\infty}$, not $\mu|100$; on the same page, first line below the first equation, the word should be "insufficient," not "sufficient;" and in the second last line on the same page, the equations should be $\omega_0 = 2\pi f_0$ and $\bar{\omega}_0 = 2\pi f_0$.

Non-magnetic sky compass for polar regions--A new non-magnetic compass which can be used for air navigation in polar regions has been developed by the National Bureau of Standards cooperating with the Navy's Bureau of Aeronautics. This should prove especially useful during the long periods of twilight when neither sun nor stars are visible in the vast polar areas where the magnetic compass, sun compass, and astro compass cannot be used. It is based on the investigations of the late A. H. Pfund of Johns Hopkins University and involves the principle of polarized light, and would ordinarily, on this basis alone, have an accuracy of about ten degrees. A "match-of-brightness" requirement increases the accuracy of one degree under favorable circumstances.

Meeting of the Eastern Snow Conference--The Third Mid-Winter Meeting of the Eastern Snow Conference was held in Greenfield, Massachusetts, February 10-11, 1949. About 50 were in attendance and 12 papers were presented. Burke L. Bigwood was elected President, Harry M. Nelson, Vice-President, and Holbert W. Fear was re-elected Secretary.

Conference on Radioactive Ores at Michigan College of Mining and Technology--On May 6, 1949, the Upper Peninsula of Michigan Mineral Industries Conference held a meeting to help coordinate and make more effective the search for radioactive ores in that region. Exploration for uranium and the use of the Geiger counter in reconnaissance were discussed in a number of papers. About 200 people were in attendance.

Second Annual Conference on Geophysics of the University of California--The Second Annual Conference of the Institute of Geophysics of the University of California was held at Scripps Institution of Oceanography May 13-14, 1949. The first day's program bore heavily on oceanography and seismology, with a dinner session on trace elements in meteorites. The second day included papers on meteorology and the upper atmosphere and a visit to one of the oceanographic vessels and its laboratories.

Appointment of Committee on Nomenclature of Ocean Bottom Features--The International Committee on the Nomenclature of Ocean Bottom Features, re-established at the meeting of the International Union of Geodesy and Geophysics at Oslo in August 1948, has been appointed with the following members: J. D. H. Wiseman of the British Museum, Chairman; J. D. Nares of the International Hydrographic Bureau, Secretary; K. O. Emery and H. H. Hess of the United States; Hans Pettersson of Sweden; and Ph. Keunen of the Netherlands. The mission of the Committee is to obtain international agreement on the nomenclature of submarine topographic features.

First voyage of naval oceanographic vessels--The USS Rehoboth and San Pablo returned to the United States in April 1949, having completed their first oceanographic cruises.

Control of water seepage--The American Petroleum Institute announces that subsurface flow can now be controlled through the injection of an aqueous emulsion of asphalt into the water-bearing strata. Chemicals mixed with the emulsion cause the asphalt to coalesce, creating an underground barrier to seepage. It is stated that the method has been used to check seepage through an earth dam in California.

Physics of the Earth Series relating to Terrestrial Magnetism and Electricity, and to Hydrology now available--New editions of Physics of the Earth Series, Volume VIII, Terrestrial Magnetism and Electricity, and Volume IX, Hydrology, have recently been issued by Dover Publications, 1780 Broadway, New York 19, New York. A special low purchase price ($4.95) has been set effective until June 30, 1949 only, with a discount (about ten per cent) for the purchase of both books at one time.

Civil Service examinations for cartographers and cartographic aids--The Civil Service Commission has announced that applications are being received for cartographic position in the P-3 to P-6 grades, and SP-2 to SP-8 grades. Most of the positions to be filled are in Washington, D. C. area, but a few are available in connection with mobile field units. Examinations are unassembled. Apply at first- and second-class post offices or write to the Civil Service Commission, Washington 25, D. C. for further information.

Civil Service examination for geologists--The United States Civil Service Commission announces that applications are still being received for geologists in the P-3 to P-6 grades in accordance with the announcement issued July 15, 1947.

Three sediment cores from the Tyrrhenian Sea--Contribution No. 15 from the Oceanographic Institute at Gothenburg (Goteborgs Kungl. Vet. Vitt. Handl., sjatte foldjen, Ser. B, v. 5, no. 13, 94 pp., 1948) contains ten papers by specialists on the physical and chemical properties and pollen and diatom content of three long cores obtained off Naples by the Skagerak in 1946 under Hans Pettersson. One core, 10.5 m long, was raised from a depth of 3620 m.

PERSONALIA

Lloyd V. Berkner, Chief of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been appointed Special Assistant to the Secretary of State to work on the Military Assistance Program being planned to aid the North Atlantic Security Pact.

Gordon M. Fair, Dean of the Graduate School of Engineering at Harvard University, has been appointed Chairman of a newly created Division of Engineering Sciences in the Faculty of Arts and Sciences to aid in the translation of pure science into the techniques of engineering.

Bent E. Holtsmark and Rexford Rowray of the U. S. Naval Electronics Laboratory, San Diego, arrived at Point Barrow, Alaska, in April 1949, to continue the joint oceanographic research program of the Office of Naval Research and the Hydrographic Office at the Artic Research Laboratory.

Walter D. Lambert, named the recipient of the Eleventh Award of the William Bowie Medal, was recently elected to the National Academy of Sciences becuase of his outstanding work in Geophysics.

Thomas S. Lovering of the United States Geological Survey was recently elected to membership in the National Academy of Sciences.

Walter C. Lowdermilk, Past-President of AGU, has recently gone to England and Africa on the soil erosion problems of British Colonial Africa. The undertaking, which will last about a year, is known as the Lowdermilk-Africa Project, and is being undertaken under the sponsorship of Agricultural Missions, Inc., the Secretary of State for the Colonies of the British Government, and British and American Missionary socieites. The problem is essentially that of erosion control and water conservation, which, among the natives of these regions, is closely related to their religion.

Harald U. Sverdrup was honored on his 60th birthday by the dedication of the third number of Volume 7 of the Journal of Marine Research to him "in appreciation of his profound influence on the development of oceanography and meteorology." The 582-page number, containing 41 papers relating to oceanography, was made possible by a grant from the Ellen Browning Scripp Foundation.

Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, D. C., was recently awarded the Cyrus B. Comstock Prize by the National Academy of Sciences for his work in nuclear physics, geophysics, and the development of the proximity fuse.

Oliver R. Wulf of California Institute of Technology, was recently elected to the National Academy of Sciences because of his outstanding scientific work in Geophysics.

Philip S. Smith, retired Chief of the Alaskan Branch, United States Geological Survey, died May 10, 1949 in St. Albans, Vermont after a brief illness. He was born in Medford , Massachusetts in 1877, received his baccalaureate degree from Harvard University in 1899, his masters and doctorate degrees from the same university in 1900 and 1904, respectively. From 1900 to 1906, he was an instructor in geology at Harvard University, following which he entered the service of the Geological Survey, rising rapidly through the various grades. From 1925 until 1946 when he retired, he was the Chief of the Alaskan Branch.

Edward B. Stephenson, Superintendent of the Mechanics Division of the Naval Research Laboratory died suddenly, May 6, 1949, in San Francisco at the age of 67. He was born in Sparta, Illinois, and received his baccalaureate and masters degrees from Knox College in 1903 and 1907, respectively. He received his doctorate from the University of Illinois in 1910, and in 1943, Knox College awarded him an honorary doctorate. His early professional years were spent in teaching in high schools and schools that he was attending. Subsequently he taught at the University of North Dakota until World War I, during which he entered the service of the Corps of Engineers as a physicist. He continued in Federal service following the War, and was associated with the Naval Research Laboratory since 1924. He had been a member of AGU since 1934.

Transactions, American Geophysical Union Volume 30, Number 3 June 1949

THIRTIETH ANNUAL MEETING (1949)

MINUTES, GENERAL ASSEMBLY AND SECTIONS

EVENING SESSION AND SYMPOSIUM

The Evening Session of the Thirtieth Annual Meeting was called to order by President Walter H. Bucher at 20^{h}10^m, Wednesday, April 20, 1949, in Elihu Root Hall, Adminstration Building, Carnegie Institution of Washington, 1530 P Street, Northwest, Washington, D. C. About 150 were in attendance. After preliminary remarks, President Bucher introduced George F. McEwen, who arranged the Symposium on Turbulence and Mixing in the Sea and Interaction between the Ocean and Atmosphere. He in turn introduced C. O'D. Iselin as Chairman and Discussion Leader of the first of two sessions of the Symposium. Four papers were presented as follows:

(1) H. Stommel: The spectrum of turbulence in the sea
(2) R. J. Urick: Microthermal variations in the ocean near Key West, Florida
(3) B. Haurwitz: Internal waves of tidal character
(4) G. F. McEwen: A statistical model of instantaneous point and disc sources with applications to oceanographic observations

There was discussion from the floor following the presentation.

Chairman Iselin then turned the Chair back to Dr. McEwen who mentioned the continuance of the Symposium in a second session to be held Friday, April 22, 1949 in the Auditorium of the Natural History Building at 14^{h}00^m.

The Chair was then returned to President Bucher. He introduced Leo O. Colbert who cited Walter D. Lambert as the Eleventh William Bowie Medalist [see pp. 321-322 of this issue for the citation]. Following this, President Bucher presented the Medal to Dr. Lambert whose response is printed following the citation.

The session was then declared adjourned, and a social hour, with refreshments, followed in the adjoining room.

AFTERNOON SYMPOSIUM AND BUSINESS SESSION

The Afternoon Session was called to order by General Secretary Beij at 14^{h}10^m Wednesday, April 22, 1949, in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. About 100 were in attendance. General Secretary Beij presented George F. McEwen who acted as Chairman of the second session of the Symposium.

Chairman McEwen introduced the speakers, and the following papers were heard:

(5) A. F. Spilhaus, A. Ehrlich, and A. R. Miller: Hydrostatic instability at the edge of the continental shelf (presented by A. F. Spilhaus)
(6) D. W. Pritchard: A review of the evaporation problem over the ocean and over smaller bodies of water, and a proposal for the investigation of certain phases of this problem
(7) A. Woodcock: Atmospheric salts over the sea
(8) I. I. Schell: A program for the study of the circulation trends in the Arctic and adjacent areas from the long series of Arctic ice observations
(9) Chung-Pen Ho: Temperature distribution in the upper ten centimeters of a water column (by title)

Following the presentation, there was discussion from the floor. Then the Chair was turned over to President Bucher who proceeded with the Business Meeting.

President Bucher introduced Francis W. Reichelderfer, our new Vice President, recently designated by the Executive Committee to complete the unexpired tern of H. U. Sverdrup who resigned because of resumption of his residence in Norway.

General Secretary Beij summarized the activities of the Union since the Twenty-Ninth Annual Meeting. These are reported in detail in connection with the Minutes of the Meeting of the

Executive Committee of December 3, 1948 [see February 1949, Trans., pp. 151-154] and April 23, 1949 [to be published in August 1949 issue of the *Transactions*]. To be noted especially here is the vote (roughly 3 to 1) favoring the raising of the upper limit of dues from $5 to $7 per annum; the fact that the cash balance as of March 31, 1949 in all accounts was $18,421.65, about $4000 less than the corresponding balance a year ago, reflecting the real need for dues increase; and a recapitulation of the membership, as follows:

Members, April 20, 1948	4290	
Inactive to active status	5	
New Members	381	
		4676
Active to inactive	8	
Resignations	92	
Deceased	26	
Dropped	101	
		227
Membership as of April 20, 1949		4449

The Annual Report of the General Secretary was accepted.

Reports of Standing Committees

Meetings--Chairman John Putnam Marble presented the report published as Appendix A of these Minutes.

Editorial and Publications--Chairman K. Hilding Beij reviewed activities of the last year briefly, reported that the *Transactions* are now being published in an edition of 5200, and that the job of indexing the first 25 years (1920-1944) of the *Transactions* has reached the editorial stage; and it is expected that the index will be published in the late fall or early winter of 1949.

It was approved that the reports be accepted.

Reports of Special Committees

Resolutions--John Putnam Marble, acting for Chairman Earl Engerson, presented eight resolutions which were unanimously adopted, as follows:

(1) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The success of the Thirtieth Annual Meeting of the American Geophysical Union, now in session, is due in large part to the space and facilities generously provided by various agencies, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the Smithsonian Institution, to the Carnegie Institution of Washington, to the United States Public Buildings Administration, and to the National Academy of Sciences for the extension of their meeting rooms and other facilities, and that the General Secretary of the Union be requested to forward to the appropriate officers of these agencies copies of this resolution.

(2) RESOLUTION OF THANKS TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years kindly furnished office, storage space, and other facilities without charge for use by the American Geophysical Union and has continued the same service for the past year, therefore be it

RESOLVED, That the American Geophysical Union expresses its sincere appreciation of this kind and generous action of the Carnegie Institution of Washington and instructs its General Secretary to express the thanks of the Union for the same to the President and Chairman of the Board of Trustees of the Carnegie Institution of Washington.

(3) RESOLUTION OF APPRECIATION TO NORWEGIAN AUTHORITIES

WHEREAS, During the Eighth General Assembly of the International Union of Geodesy and Geophysics held at Oslo from August 19 to 28, 1948, the Norwegian Government provided for a special excursion to Lillihammer for the delegates, and

WHEREAS, The officials of the City of Oslo entertained the delegates at a reception at Akershus Castle, and

WHEREAS, The Norwegian Organizing Committee arranged for many interesting meetings in addition to planning for the accommodations of the delegates, therefore be it

RESOLVED, That the American Geophysical Union express its deep appreciation for these and other kindnesses shown the American delegates while they were visiting in Norway, and instruct its General Secretary to express the thanks of the American Geophysical Union to the appropriate Norwegian authorities.

(4) RESOLUTION ON COMMUNICATIONS SERVICES

WHEREAS, The Secretary of Commerce in cooperation with the Foreign Service Office of the United States, the officers of the Foreign Service, and the Foregin Service Operations Staff of the Office of International Trade, have made available their special telegraphic facilities for transmitting teleseismic data to the United States Coast and Geodetic Survey, and

WHEREAS, The data have greatly accelerated and expanded the earthquake location program of the United States Coast and Geodetic Survey, and

WHEREAS, The data are made available by the United States Coast and Geodetic Survey to seismologists throughout the world to aid in the more thorough analysis of their records, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation for this valuable contribution to seismological research, and be it further

RESOLVED, That copies of this resolution be funished the Secretary of Commerce, the Foreign Service office of the United States, the Foreign Service Operations Staff of the Office of International Trade, and the officers of the Foreign Service at the following stations: Antofagasta, Chile; Batavia, Java; Bombay, India; Brisbane, Australia; Cairo, Egypt; Copenhagen, Denmark; Damascus, Lebanon; Guatemala City, Guatemala; La Plata, Argentina; Lima, Peru; Malaga, Spain; Mexico City, Mexico; Perth, Australia; Rio de Janeiro, Brazil; Rome, Italy; Santiago, Chile; Strasbourg, France; Sydney, Australia; and Tananarive, Madagascar.

(5) RESOLUTION OF TIME SIGNAL SERVICE

WHEREAS, There is a vital need in all seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communications Service, and the National Bureau of Standards, has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of the valuable scientific cooperation and desire for its complete continuance, and be it further

RESOLVED, That copies of this resolution be sent to the Secretary of the Navy, the Director of the Naval Communication, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(6) RESOLUTION OF MEASUREMENT OF GRAVITY AT SEA

WHEREAS, Through the cooperation of the Office of Naval Research, Navy Department; the Commander, Submarine Force, United States Atlantic Fleet; the Commander, Submarine Force, United States Pacific Fleet; and Columbia University, the measurement of gravity at sea has been extended during the last year on the continental margin in the Straits of Florida and along the Atlantic Coast from Florida to Cape Hatteras; and two trans-Pacific gravity profiles have been made from San Diego to Hawaii to China, and one gravity profile from San Diego to the Canal Zone to Key West.

WHEREAS, The value of this gravity-at-sea project increases rapidly as further work is accomplished, and

WHEREAS, A part of the scientific expense of this work was borne by the Office of Naval Research which has underway an extensive program for the measurement of gravity at sea, by contract with Columbia University, and

WHEREAS, The basic instrumental equipment, the Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer, were supplied by the Woods Hole Oceanographic Institution, and

WHEREAS, Additional apparatus was furnished by Columbia University, therefore be it

RESOLVED, That the American Geophysical Union express its approval of this project and urge its continuation, and therefore be it further

RESOLVED, That copies of this resolution be sent to the Chief, Office of Naval Research; the Commander, Submarine Force, United States Atlantic Fleet; the Commander, Submarine Force, United States Pacific Fleet; the Commanding Officers of the submarines Medregal, Capitaine, Bergall, and Chopper which were engaged on this work; the President of Columbia University; the Director, Woods Hole Oceanographic Institution; the Bell Telephone Labroatories; and to Maurice Ewing and the other members of the scientific party engaged in this work (J. L. Worzel, C. L. Drake, and J. G. Heacock, of Columbia University).

(7) RESOLUTION OF GRAVITY VALUES IN SOUTH AMERICA

WHEREAS, P. C. Wuenschel has been supported by the Office of Naval Research, Navy Department; and Inter-American Geodetic Survey in observing a network of gravity values on several profiles across South America.

WHEREAS, This project when completed will be of great value to the geophysical sciences, therefore be it

RESOLVED, That the American Geophysical Union express its approval to the Chief of Naval Research and the Director of the Inter-American Geodetic Survey, and urge continuation of similar projects in the future, and be it further

RESOLVED, That copies of this resolution be sent to the Chief of Naval Research, Director of the Inter-American Geodetic Survey, President of Columbia University, Maurice Ewing, and P. C. Wuenschel of Columbia University.

(8) RESOLUTION ON EXTENSION OF GRAVIMETRIC NET

WHEREAS, G. P. Woollard has been supported by the Office of Naval Research, Navy Department, in extending the gravimetric net of world base stations,

WHEREAS, This project when completed will be of very great value to the geophysical sciences, and

WHEREAS, This project has been completed to the extent that many gravity base stations in the northern hemisphere have been tied together, therefore be it

RESOLVED, That the American Geophysical Union express its approval and urge the Chief of Naval Research to take favorable action concerning its continuation and expansion into the southern hemisphere, and be it furtheer

RESOLVED, That copies of this resolution be sent to the Chief of Naval Research; President, University of Wisconsin; and to G. P. Woollard, University of Wisconsin.

The other reports of Special Committees were ready by title with the understanding that they would be published in the Transactions as they become available. The reports of the Committees on Cosmic Terrestrial Relationships and for the study of Tsunamis are published as Appendices B and C, respectively.

Reports of Secretaries of Sections

These reports were presented by title, and are found in Appendices D to K.

Adjournment--The meeting adjourned at 16^h20^m.

SMOKER

A Smoker was held in the Auditorium of the Cosmos Club Friday, April 22, 1949 from 20^h00^m to 22^h30^m. About 100 were in attendance. The affair was informal, with no program, but offered opportunity to get together with old friends and new acquaintances to fulfill one of the valuable functions of annual meetings. Discussion was lively in the various groups.

APPENDIX A--REPORT OF THE COMMITTEE ON MEETINGS

John Putnam Marble, Chairman

J. A. Duerksen   O. W. Torreson   Frank J. Veihmeyer
Nicholas A. Rose   Merle A. Tuve   George G. West

Since our last report one regional meeting was held in Los Angeles, California on February 4 and 5, 1949, at which the Sections of Meteorology and Hydrology held sessions.

The Thirtieth Annual Meeting was held in Washington, D. C. on April 20-22, 1949. All sections met. A total of 117 papers and research reports were presented at 16 sessions, five of which were joint sessions or general symposia. It is hoped to continue joint-session arrangements. One session of the symposium was combined with the award of the William Bowie Medal and a social hour, the other preceded the Business Meeting. A well-attended smoker took place at the Cosmos Club Auditorium on the evening of April 22, 1949.

The total registered attendence was about 800, and the estimated attendance was about 1000. Meeting rooms were supplied through the courtesy of the United States National Museum, the Carnegie Institution of Washington, the Public Buildings Administration, and the National Academy of Sciences.

The Thirty-First Annual Meeting will be held in Washington on May 1-4, 1950. This slightly later date will avoid conflicts with certain other organizations.

A joint meeting of the Section of Hydrology with the Western Snow Conference has been scheduled for April 26-27, 1949, to be held in Denver, Colorado.

Through overlapping membership and otherwise, cooperative contact has been maintained with the Committee on Regionalization. It is hoped that it will soon be easier to organize regional meetings of Sections or of the Union.

The Committee takes this occasion to thank the Section and Union officers and others for their continued cooperation.

APPENDIX B--REPORT OF COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR 1948-1949

The work of the Committee on Cosmic-Terrestrial Relationships has continued along the several lines which it is the object of the Committee to promote. The laboratory at Needham has continued to place major emphasis upon the relation of solar activity and meteorological phenomena to radio wave propagation; in the one instance, by way of the ionosphere and in the second instance, by way of the troposphere. Sunspot activity, which reached a peak in the summer of 1947, retreated sharply to the early part of 1948, but staged a remarkable recovery to a second peak in the summer of 1948, being a little less than that of the 1947 maximum. This was followed by another marked drop with a subsequent rise with a third peak in the early part of 1949.

With solar activity still high, radio-wave propagation has, in general been characteristic of a high degree of ionization in both the E and F layers. There are now in operation at Needham eight radio-field intensity recorders; hourly data of six have been reduced, analyzed, and forwarded to the Central Radio Propagation Laboratory of the National Bureau of Standards, with which the laboratory is associated.

A continued study of the long series of records of WWV five megacycles, as received at Needham, has shown systematic trends in the hourly values throughout the sunspot cycle from 1942 to date. Midnight values rose from a sunspot minimum of about 100 microvolts in 1944 to 1000 microvolts in 1948, whereas midday values dropped from a maximum of around 200 microvolts in 1944 to a minimum of about 100 microvolts since midsummer of 1947, corresponding closely with the sunspot peak. Noonday values have been slowly rising since that time.

In addition to the laboratory's own calibrations, outside engineers have investigated extensively the recordings at the Needham laboratory. Representatives of the National Bureau of Standards have visited the laboratory for independent calibration with their own standard equipment. They report little evidence for any systematic errors and have stated that observational errors are probably less than one decibel. This is an order of accuracy that could be expected to obtain. The long series of field-intensity records made, increase in value with each additional year of accumulated data and will ultimately furnish an independent basis for anticipating changes in field intensities over given distances and at given frequencies, a series of data which stands on the basis of actual measured performance irrespective of the mode of transmission employed.

Comparisons in fields obtained from WWV five megacycles at Needham have been made with those obtained at Intervale, New Hampshire, at New Haven, Connecticut, and with a field station at Westchester County, New York. During the summer of 1948, an auxiliary field station was again in operation at Intervale, New Hampshire for checking the 15 mc frequency reception against the diurnal pattern obtained at Needham. The results were consistent with what might be anticipated from the behavior of the lower frequencies previously compared at Intervale, New Hampshire with those obtained at Needham.

G. W. Pickard of our Committee has continued an analysis of both ionospheric and tropospheric reception, and, in an extensive harmonic analysis, has shown a well-defined, semi-lunar synodic period of 14.765 days in the WWV five megacycles night fields at Needham and over other paths and at other frequencies. Night-time fields tend to reflect probable tidal effects in the ionosphere with maxima at new and full moon for the five megacycles reception from WWV.

Tropospheric reception along the over-the-horizon 167-mile path from Alpine, New Jersey has continued to show marked correlation with meteorological changes. Through a stay of order, it has been possible to continue to make observations of the 44.1 mc frequency of W2XMN, which had been scheduled for closing off the air December 31, 1948 at the time when the new allocated frequencies of the Federal Communications Commission went into operation. The temporary continuance of this series has been of considerable value on account of the winter patterns of reception during 1947 and 1948, being materially different from that of the previous year.

From the same location at Alpine, field-intensity records have been continued from the 92.1 mc frequency until the change in allocation frequency to 93.1 mc forced our substitution of station WHYN, Holyoke, Massachusetts on the same frequency, distant 75 mi. Meanwhile, an especially sensitive recorder has been put into operation for recording the 104.9 mc band from the new Alpine antenna, giving us over-the-horizon reception at a still higher frequency.

Charles F. Brooks, Director of Harvard's Blue Hill Observatory, reports that, in cooperation with the United States Weather Bureau, continuous records of total insolation on a horizontal surface and on a vertical surface facing south, of diffuse insolation on a horizontal surface, and of the intensity of the solar beam at normal incidence, have continued throughout the past 12 months. These records, except vertical south and diffuse, now in their fourth year, are in their 17th year. The Weather Bureau has been restandardizing pyrheliometers both for themselves and for the Eppley Laboratory, Inc. A new, water-proof tube for the solar beam at normal incidence, and pyrheliometers facing E, W, and N are about to be installed. Some comparisons between observations in (smoky) Boston and at Blue Hill, and a study of the transmission of insolation by different types of clouds, have been made by Irving F. Hand and Bernhard Haurwitz, respectively.

Irving F. Hand, Meteorologist in charge of the Weather Bureau's Solar Radiation Supervising Station at Blue Hill reports that most of the equipment for 40 solar stations has been installed and is awaiting checking by electronic technicians of the Weather Bureau and himself. In addition, new solar equipment will soon be added outside continental United States, as, for example, Canton Island, 2 3/4° S, and at a point within ten degrees of the North Pole. Old equipment at a number of long established stations has been replaced with modern apparatus. Routine observations of aurora continue (65th year) at Blue Hill Observatory.

Members of your Committee have attended major conferences during the year. J. H. Dellinger attended the Stockholm meeting of the International Radio Consultive Committee in July 1948. D. H. Menzel, after attending the Geneva meeting of the International Astronomical Union in the summer of 1948, attended a conference at Cornell University on cosmic and solar noise in October 1948. Meetings of the Institute of Radio Engineers and the American Section of the URSI have been represented by three members of your Committee, J. H. Dellinger, G. W. Pickard, and the Chairman. J. A. Fleming though retired from the directorship of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, has continued to be of much assistance to the work of the Committee. J. H. Dellinger, whose services have been most valuable, retired as Chief of the Central Radio Propagation Laboratory at the National Bureau of Standards in 1948. S. A. Korff, who has vigorously pursued cosmic ray studies, is now in Europe surveying research in his field in that area.

Probably one of the most outstanding new developments in instrumentation of the year and one which should be of great significance in geophysical investigations is the atomic clock, that has been constructed and set up at the National Bureau of Standards, This is probably as far in advance of the crystal clock as was the quartz oscillator timepiece ahead of the best Shortt clock of the pendulum type that had been previously developed. The atomic clock presumably will eliminate the uncertainty of drift in the quartz oscillator by means of auxiliary controlled circuits which depend for their operation upon the absorption of microwaves by a band in the absorption spectrum of ammonia gas. With the problem of drifting frequency essentially removed, it is believed that the atomic clock will make possible an order of precision in time measurement of from one part in ten million to one part in a billion, or even possibly ten billion. The significance of the new development is that the rotating Earth as a standard of time may already have become obsolete and we have instead a precision timepiece suitable as a means for checking irregularities in the Earth's rotation, star positions, and small variations in longitude previously undetectable because of the necessary uncertainties involved in the timepieces employed.

W. T. Thom of our Committee points out that much of his work for the past year has been centered in an area of research which may well prove to have a bearing upon that cosmic-terrestrial problem. From fragmentary evidence now at hand, it appears that alternations of the Earth's crustal behavior including volcanic activity and deep focus earthquakes are activated by recurrent chain reactions taking place within the Earth. It should appear possible in the not-too-distant future that with the use of the atomic clock and high precision astronomic determinations of latitude and longitude that the question of small but slow Earth movements producing shifts in geographical coordinates may be resolved and such change become more definitely demonstrable than it has been heretofore. Thus astronomy and geology through electronic instrumentation may come together in the development of a problem of cosmic-terrestrial relationships of marked geophysical significance.

HARLAN T. STETSON, Chairman

APPENDIX C--REPORT OF COMMITTEE FOR THE STUDY OF TSUNAMIS

This Committee was designated the Special Committee for the Study of Tsunamis at the Meeting of the Executive Committee on December 3, 1948 as the successor of the former Special Committee for Cooperation with the International Commission for the Study of Tidal Waves. The newly designated Committee has the same membership as the previous Committee. The Committee was authorized to pursue a suitable program without the expenditure of AGU budgeted funds.

The Committee has considered ten areas of activity and has concluded that the following show most promise of useful results under prevailing circumstances.

(1) To suggest to appropriate authorities studies of details of the tsunami phenomenon as subjects for graduate work in universities.
(2) Preparation of a comprehensive bibliography on tsunamis and related phenomena.
(3) Periodic listing of research and study in progress, with statements of personnel and sponsoring agencies.
(4) Prepare a statement of needed research and study.

In the event that funds should become available to the Committee, it is considered that expansion of support into more active phases of study would be desirable. The Committee is not prepared presently to request a budget, reserving such action until the need becomes more urgent.

The Committee will undertake organization of a symposium on tsunamis at an appropriate time.

The Scripps Institution of Oceanography is operating two ultra low frequency wave recorders; one located at La Jolla, California, the other on the island of Maui, Territory of Hawaii. A third installation is planned for Oceanside, California, which, in conjunction with the La Jolla station, should permit some determination of direction of travel of low frequency waves.

The United States Coast and Geodetic Survey now has in operation a seismic sea-wave warning system in the Pacific. It consists of the detection and location of earthquakes by Coast and Geodetic seismograph stations, automatic seismic sea-wave detectors installed at certain tide stations, and a high priority communication system provided by the military services and the Civil Aeronautics Administration. The headquarters of the system is located at the Coast and Geodetic Survey observatory near Honolulu, where all reports are received and evaluated.

The Coast and Geodetic Survey has continued to maintain its file of seismic sea-wave records; some 130 records were examined for waves during the past year. A wave originating in the Tonga Island region on September 8, 1949 was recorded at Honolulu, Port Allen, Waianae, and Pago Pago.

Publications of particular interest are: An Instrument for Recording Ultra Low Frequency Ocean Waves, by Munk, Iglesias, and Folsom, appearing in the Review of Scientific Instruments for October, 1948, and The Tsunami of April 1, 1946 in the Hawaiian Islands by MacDonald, Shepard, and Cox, Publication 3929, Smithsonian Institution.

MARTIN A. MASON, Chairman

APPENDIX D--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Thirtieth Annual Meeting of the Section of Geodesy was called to order by President H. W. Hemple, at $13^{h}33^{m}$, April 20, 1949, in Conference Room B, Interdepartmental Auditorium, Washington, D. C. About 125 members and guests were in attendance.

The minutes of the Twenty-Ninth Annual Meeting were declared approved as published in the Transactions [v. 29, pp. 440-442, 1948].

N. F. Braaten, Editor for the Section of Geodesy, reported that only one paper presented at the last annual meeting had not been published. He invited members to submit to the Secretary at any time new papers and discussions of those published.

J. B. Small, the Section's Membership Committeeman, reported on the increase of membership of the American Geophysical Union.

R. M. Wilson, Chairman of the Resolutions Committee, submitted three resolutions which were recommended by the Section to be adopted by the Union [see Minutes of the Business Meeting of the Union preceding appendices].

W. D. Sutcliffe, Chairman of the Nominations Committee, reported the nomination of Charles A. Whitten for United States member of the Permanent Commission of the International Association of geodesy vice Walter D. Lambert who had resigned effective with the election of his successor. No other nomination was made and Whitten was elected unanimously.

Walter Davis Lambert was presented the Department of Commerce's Gold Medal for exceptional service in Scientific Geodesy and the 40-year service button in behalf of the Secretary of Commerce.

After routine announcements, the following scientific papers were presented:

(1) C. A. Whitten: Report on adjustment of European adjustment
(2) T. Nicholas Panay: Measurement of 1948 eclipse photographs
(3) Perry Byerly: Geodetic observations in the solution of geodetic problems
(4) G. P. Woollard: World-wide measurements with a gravimeter
(5) F. W. McBryde: A statistical world projection
(6) Thaddeus Skowron: Punch-card method of converting geographic coordinates to universal transverse Mercator grid coordinates
(7) Clarence W. Kitchens: Automatic computing machines for traverse computations
(8) Charles R. Hoover: Development of an optical radar system for surveying purposes
(9) P. C. Doran: Geodetic surveying in Latin America
(10) Manuel Medina P.: Geodetic work in Mexico from April 1948 to March 1949 (by title)
(11) A. J. Hoskinson: Progress in geodetic surveys by U. S. Coast and Geodetic Survey since July 1948 (by title)
(12) Walter D. Lambert: The International Association of Geodesy

The meeting adjourned at 18^h05^m.

FRANK L. CULLEY, Secretary

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Thirtieth Annual Meeting of the Section of Seismology was held on Thursday, April 21, 1949 in Conference Room B of the Interdepartmental Auditorium, Washington, D. C. The meeting was called to order by President Frank Neumann, promptly at 09^h00^m. The minutes of the last meeting were approved as published in the Transactions [v. 29, pp. 442-443, 1948].

L. M. Murphy (Chairman), H. Freeborn Johnston, and William J. Rooney were asked to serve as the Committee on Resolutions. The Committee was asked to report following a brief intermission in the Scientific portion of the program which was scheduled for approximately 10^h30^m.

R. R. Bodle (Chairman), Beno Gutenberg, and James B. Macelwane were appointed as the Committee on Nominations for Officers of the Section for the next trienium. The President called attention of the members present that nominations for officers of the Union should be made well in advance in November 1, 1949 in conformance with the procedures for the nomination and election of officers as published in the Transactions for December 1946 [pp. 911 and 912].

Since there was no other old or new business, the Business Session was adjourned at 09^h07^m and was followed immediately by the following schedule of scientific papers.

(1) J. B. Macelwane and Ross R. Heinrich: Report of the Jesuit Seismological Association for 1948 (presented by J. B. Macelwane)
(2) B. Gutenberg, C. F. Richter, and H. Benioff: Earthquake study in Southern California, 1948 (presented by B. Gutenberg)
(3) Enrique Silgado F.: Seismology in Peru
(4) L. H. Adams, G. L. Davis, J. L. England, R. W. Goranson, J. B. Doak, W. J. Rooney, H. Tatel, M. A. Tuve, J. H. Harrell, W. J. Hume, II, E. J. Workman, M. Ewing, S. Katz, and F. Press: Seismic observations to 300 kilometers from explosions up to one ton (presented by L. H. Adams)
(5) W. J. Rooney, H. Tatel, R. W. Goranson, and J. W. Greig: Distant seismic observations from large TVA blasts (presented by W. J. Rooney)
(6) H. Tatel: Direct determination of seismic wave types
(7) H. Tatel, W. J. Rooney, and R. W. Goranson: Analysis of seismic records (presented by H. Tatel)
(8) D. S. Carder, L. M. Murphy, T. H. Pearce, and A. E. Lamison: Observations by the U. S. Coast and Geodetic Survey on the TVA blast of February 5, 1949 (presented by D. S. Carder)
(9) James T. Wilson and William R. Drake: Travel times and amplitude ratios of surface-reflected shear waves (presented by James T. Wilson)
(10) W. M. Elsasser and I. Isenberg: Constitution of the Earth's central region (presented by W. M. Elsasser)
(11) Carl Kisslinger: Velocity of longitudinal waves in some Paleozoic formations in the vicinity of St. Louis, Missouri

Vice-President Perry Byerly presided after a ten-minute intermission following paper (7). The Committee on Resolutions presented three resolutions which were approved for transmission to the Committee on Resolutions of the Union. (These resolutions were adopted by the General Assembly during its Thirtieth Annual Meeting on April 22, 1949 and are published in this issue with the other resolutions adopted.)

The 1949 Meeting of the Section of Seismology formally adjourned at 12^h30^m. About 150 were in attendance and those present agreed that the meeting was most pleasant and profitable.

FLORENCE ROBERTSON, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Thirtieth Annual Meeting of the Section of Meteorology was held April 20 and 21, 1949, in the Auditorium of the National Academy of Sciences and Natural History Building of the National Museum, Washington, D. C. Nearly 400 members and guests attended the several sessions.

The opening business session was held from 09^h15^m to 09^h30^m, April 20, 1949, with President Horace R. Byers presiding. Since no corrections were received, the President declared the minutes of the Twenty-Ninth Annual Meeting of the Section of Meteorology approved as published in the Transactions [v. 29, p. 443, June 1948]. The President then appointed a Committee on Resolutions (Werner A. Baum, Chairman; Sidney Teweles, Jr.), and a Committee on Nominations (C. F. Brooks, Chairman; C. W. Thornthwaite; R. H. Weightman; H. R. Byers, ex-officio).

The membership voted to designate the President of the Section of Meteorology as voting delegate for the United States in the Association of Meteorology of the International Union of Geodesy and Geophysics. In case of the President's non-attendance at an Association meeting it is provided that he shall name an officer or member as voting delegate in his stead.

The opening scientific session was held from 09^h30^m to 11^h30^m, April 29, 1949, under the Chairmanship of Charles H. Pierce and consisted of a Symposium on Meteorological Measurements.

The second session, meeting from 14^h00^m to 17^h00^m, on April 20, was held jointly with the Section of Hydrology and under the Chairmanship of H. E. Landsberg.

The third session, meeting from 09^h00^m to 12^h00^m on April 21, was held jointly with the Section of Terrestrial Magnetism and Electricity and the American Meteorological Society and consisted of a Symposium on Thunderstorms under the Chairmanship of A. F. Merewether.

The scientific program for the three sessions consisted of the following papers:

First session, Wednesday morning, April 20, 09^h30^m, Charles H. Pierce, Chairman, Symposium on Meteorological Measurements.

(1) H. J. aufm Kampe: Visibility and water content of clouds in the free atmosphere
(2) J. R. Gerhardt: A simple integrating device for the routine statistical analysis of recorded data
(3) W. E. Knowles Middleton: The effect of the angular aperture of a telephotometer on the telephometry of collimated and non-collimated beams
(4) Donald C. Bunting and Marinus H. Latour: Weather radar studies in Ohio
(5) Lester A. Zurcher: Storm detection radar
(6) William B. Gould: Cloud detection by radar

Second session, Wednesday afternoon, April 20, 14^h00^m, Helmut E. Landsberg, Chairman, held jointly with Section of Hydrology.

(7) C. C. Bates and G. G. Lill: Current naval research in sea and land ice
(8) R. D. Fletcher: A relation between maximum observed point and areal rainfall depths
(9) G. S. Benton, R. T. Blackburn, and V. O. Snead: The role of the atmosphere in the hydrologic cycle (presented by G. S. Benton)
(10) U. Nakaya: Snow crystals and frost flowers (presented as a sound film)

Third session, Thursday morning, April 21, 09^h00^m, Arthur F. Merewether, Chairman, Symposium on Thunderstorms, held jointly with Section of Terrestrial Magnetism and Electricity, and the American Meteorological Society.

(11) Horace R. Byers: Relative areas of thunderstorm turbulence at high altitudes
(12) Roscoe R. Braham, Jr.: Thermodynamics of the thunderstorm
(13) Horace R. Byers: The downdraft and surface outflow of the thunderstorm
(14) Joachim Kuettner: The electrical and meteorological conditions inside thunderclouds
(15) E. J. Workman: Electrical properties of thunderstorms and a suggested method of charge generation

WOODROW C. JACOBS, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Thirtieth Annual Meeting of the Section of Terrestrial Magnetism and Electricity of the American Geophysical Union was held on April 21 and 22, 1949. There were two joint sessions and two sessions devoted primarily to this Section. At 09^h00^m on April 21, our Section joined with the Section of Meteorology and the American Meteorological Society for a Symposium on Thunderstorms [see minutes of Section of Meteorology, above]. At 14^h00^m on April 21, this Section met jointly with the Section of Tectonophysics to hear a group of three papers that concerned both Sections [see minutes of Section of Tectonophysics, Appendix K]. The first separate session of the Section of Terrestrial Magnetism and Electricity was called to order at 15^h20^m on Thursday, April 21, 1949, in Conference Room B of the Interdepartmental Auditorium, with President Irwin Roman occupying the chair. There were about 175 members and guests in attendance. The minutes of the previous meeting, as published in the Transactions [v. 29, p. 444, June 1948] were approved. After routine announcements, the following four papers were presented:

(1) L. R. Alldredge and W. J. Dichtel: Interpretation of Bikini Atoll magnetic data
(2) E. O. Schonstedt and H. R. Irons: Airborne magnetometer for determining all magnetic components
(3) Roland G. Henderson and Isidore Zietz: The upward contination of anomalies in total magnetic intensity fields
(4) F. W. Lee and Rudolph Raspet: Some observations on electrical current fields

There was informal discussion from the floor following papers (2) and (3). The session was concluded at 16^h36^m.

The final session was convened in the same room at 09^h09^m on Friday, April 22, 1949. At this session the following papers were presented:

(5) G. R. Wait and O. H. Gish: Results of electric surveys over thunderstorms
(6) Ross Gunn: A new apparatus and its use in the determination of the free electrical charge on thunderstorm rain
(7) Ralph Stair: Seasonal variations in ozone at Washington, D. C.
(8) Jack N. Brown: Round-the-world propagation at very low frequencies
(9) Gladys R. White and R. F. Potter: Application of ionospheric data at antipodal points
(10) M. W. Jones: Thickness of winter F-layer in polar regions (presented by S. L. Seaton)
(11) S. L. Seaton and D. C. Wilder: Seasonal variation in rate of electron production for the ionospheric F-layer at College, Alaska
(12) Elliott B. Roberts: Current magnetic work of the United States Coast and Geodetic Survey (by title)

There was informal discussion of various points concerning each of the papers. The meeting was adjourned at 11^h45^m.

DAVID G. KNAPP, Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Thirtieth Annual Meeting of the Section of Oceanography was held April 21, 1949, in the Auditorium of the National Academy of Sciences, Washington, D. C. The session convened at 14^h00^m and adjourned at 16^h15^m. President George F. McEwen presided.

As there were no corrections or additions proposed to the minutes of the previous Annual Meeting, published in the Transactions [v. 29, p. 445, June 1948], they were considered as approved. The scientific program consisted of the presentation and discussion of the following papers:

(1) L. O. Colbert: Oceanographic activities of the U. S. Coast and Geodetic Survey
(2) R. H. Fleming and C. C. Bates: Oceanographic program of the U. S. Navy Hydrographic Office, 1946-1949
(3) E. C. LaFond: Oceanographic research at U. S. Navy Electronics Laboratory
(4) D. W. Pritchard: Formation of the Chesapeake Bay Institute, and plans for the study of the physical hydrography and chemical properties of estuary waters
(5) J. P. Tully: Review of Canadian Pacific oceanography since 1938
(6) E. B. Callaway: Graphical determination of specific volume anomalies and currents
(7) F. L. Blue, Jr.: Diffraction of waves passing through a breakwater gap
(8) W. C. Krumbein and L. E. Ohsiek: Pulsational transport of sand by shore agents

The following papers were read by title:

(9) F. E. Browning: A new analysis of ocean and atmospheric tides and currents (by title)
(10) J. W. Johnson: Relations between wind and waves, Abbotts Lagoon, California (by title)

Attendance of members and guests at the Session exceeded 100. In addition to the papers presented at this Session a number of items concerning oceanography or directly related thereto were presented in the general Symposium sponsored by the Union.

R. H. FLEMING, Secretary

APPENDIX I--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was called to order by President Wilbur S. Burbank, April 20, 1949 at 09^h25^m, in the Conference Room B, Interdepartmental Auditorium.

The minutes of the previous Annual Meeting had been published in the Transactions [v. 29, p. 446, June 1948], and as no corrections were received they were approved. The Secretary announced the appointment of a nominating committee consisting of J. F. Schairer, Chairman, Howel Williams, and H. H. Hess.

The morning session, comprising eight papers, was as follows:

(1) Robert R. Coats: Differentiation of the Tertiary and Quarternary rocks of the Adak and Kanaga Islands, Aleutian Arc, Alaska

(2) Francis Birch, L. C. Graton, and G. C. Kennedy: Temperatures of geysers in Iceland and Yellowstone Park (presented by Francis Birch)
(3) L. C. Graton: Thoughts on the geyser mechanism
(4) Wm. F. Foshag: Lavas of Parícutin Volcano
(5) J. G. Broughton: Observations on the intrusion of rock salt by peridotite
(6) T. P. Thayer and R. L. Hay: Preliminary notes on middle and late Miocene volcanism in the John Day region, Oregon (presented by T. P. Thayer)
(7) Gordon A. Macdonald: An account of the 1949 eruption of Mauna Loa (read by Clarence S. Ross)
(8) S. J. Shand: History of a feldspar crystal

The meeting adjourned at $12^{h}30^{m}$.

FRANCIS G. WELLS, Secretary

APPENDIX J--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

Secretary Linsley called the meeting to order at $09^{h}15^{m}$, April 20. In the absence of President Lorenz G. Straub, the Secretary reported on the meetings of the International Association of Scientific Hydrology in Oslo during August 1948, and announced the election of Merrill Bernard as President of the International Association of Hydrology for the 1948-1951 triennium.

The appointment of R. W. Davenport as Chairman of the Nominating Committee for the Section of Hydrology was announced. Nominations should be in the hands of the Executive Secretary by October 1949.

The Secretary also announced the selection by the Committee on Honors and Awards of the following papers for the annual awards of the Section of Hydrology:

Best paper of 1948: Snow layer density changes, by Mr. R. A. Work [Trans., August 1948].
Best first paper of 1948: Size of raindrops and their striking force at the soil in a red pine plantation, by Gordon Chapman [Trans., October 1948].

There being no further business the Secretary turned the meeting over to A. L. Cochran as Chairman for the first scientific session. The following program was presented:

(R1) L. V. Wilcox: Report of the Research Committee on Chemistry of Natural Waters (by title)
(R2) H. G. Wilm: Report of the Research Committee on Evaporation and Transpiration
  (1) A. F. Meyer: Evapotranspiration from ground-water fluctuations (discussion by R. H. Brown)
  (2) H. G. Wilm: How long should experimental watersheds be calibrated?
(R3) F. T. Mavis: Report of the Research Committee on Dynamics of Streams (by title)
(R4) S. W. Lohman: Report of the Research Committee on Groundwater (presented by H. E. Thomas)
  (3) R. C. Baker: An occurrence of saline ground water on Guadalcanal (presented by C. L. McGuinness)
  (4) N. J. Lusczynski: Large recovery of ground-water levels from June 1947 to December 1948, in Brooklyn, New York
(R5) W. O. Fields: Report of the Research Committee on Glaciers
(R6) J. L. Hough: Report of the Research Committee on Lakes (by title)

The session recessed at $11^{h}30^{m}$.

Chairman H. E. Landsberg called a joint session of the Sections of Meteorology and Hydrology to order at $14^{h}00^{m}$ and introduced the papers as set in the minutes of the Section of Meteorology. The session adjourned at $16^{h}00^{m}$.

The morning session of April 21 was called to order by Chairman C. F. Izzard at $09^{h}15^{m}$, and the following papers and reports were presented:

(R7) W. C. Lowdermilk: Report of the Research Committee on Land Erosion (by title)
  (5) H. W. Anderson: Flood frequency and sedimentation from forest watersheds (read by E. A. Johnson)
  Discussion by Leonard Schiff

(6) Kamalesh Ray: On the sedimentation velocities of non-spherical particles (by title)
(7) M. A. Mason: A manometric settling velocity tube
(8) J. S. McNown and Jamil Malaika: Particle shape and settling velocity (presented by J. S. McNown)
(R8) Merill Bernard: Report of the Research Committee on Precipitation
(9) W. D. Potter: Effects of rainfall factors on magnitude and frequency of peak-surface runoff
(10) R. K. Linsley, Jr., and Max A. Kohler: Predicting the runoff from storm rainfall (presented by R. K. Linsley)
(11) Merrill Bernard: Developments in international hydrology
(12) N. W. Cummings: Pans as indicators of lake evaporation
Discussion by L. P. Harrison

The session recessed at 12^{h}45^{m}.

J. W. Dixon, Chairman for the afternoon, called the group to order at 14^{h}10^{m} and introduced the following papers and reports:

(R9) R. C. Farrow: Report of the Research Committee on Snow (by title)
(13) B. L. Hansen: Radio-active isotypes for measuring water equivalent of snow on the ground (presented by L. W. Foskett)
(R10) G. W. Musgrave: Report of the Research Committee on Infiltration (by title)
(R11) L. A. Richards: Report of the Research Committee on Physics of Soil Moisture (by title)
(14) Ned Bethlahmy and I. C. Reigner: Factors affecting the formation of concrete frost (presented by Ned Bathlahmy)
(15) L. A. Richards: The laws of soil moisture (by title)
(R12) C. C. McDonald: Report of the Research Committee on Runoff (by title)
(16) D. E. Whelan: Flood reductions on large watersheds by a land-use program
Discussion by W. C. Ackermann (read by Leon Lassen)
(R13) C. E. Jacob: Report of the Research Committee on Permeability
(17) Leonard Schiff and F. R. Dreibelbis: A report of preliminary studies on soil permeability and its application (presented by Leonard Schiff)
(18) C. E. Jacob and M. S. Hantush: Plane potential flow of ground water with linear leakage; I: Theory (presented by C. E. Jacob)

At the conclusion of the scheduled program the Chairman opened the meeting for general discussion. The meeting was adjourned at 16^{h}15^{m}.

RAY K. LINSLEY, JR., Secretary

APPENDIX K--MINUTES OF THE ANNUAL MEETING OF 1949, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held on Friday morning, April 22, 1949 in Conference Room B, Interdepartmental Auditorium. The meeting was called to order by President M. King Hubbert at 09^{h}10^{m}. The minutes of the previous meeting were approved as published in the Transactions [v. 29, p. 448, June 1948] The President announced the appointment of a Committee on Nominations. After routine announcements, the Business Meeting was adjourned and the second session of scientific papers was presented, the first session having been held jointly with the Section of Terrestrial Magnetism and Electricity on Thursday afternoon, April 21, 1949 at 14^{h}00^{m}.

The following papers were presented at the two scientific sessions:

First session, jointly with the Section of Terrestrial Magnetism and Electricity, April 21, 14^{h}00^{m}, M. King Hubbert, Chairman.

(1) John W. Graham: Stability of magnetization of certain sedimentary rocks
(2) O. W. Torreson, Thomas Murphy, and J. W. Graham: The magnetic polarization of sedimentary rocks in the western United States
(3) J. R. Balsley, Jr.: Aeromagnetic profiles of the northern Peninsula of Michigan

Second session, April 22, 09^{h}10^{m}, President M. King Hubbert presiding.

(1) Ralph Digman: Triassic-crystalline fault contact in Connecticut
(2) A. L. Howland and J. W. Peoples: Some structural problems of the Stillwater Complex, Montana (presented by J. W. Peoples)

(3) Richard B. Palmer: Triassic tectonics in Maryland
(4) Sam L. Agron: Deformation in the Peach Bottom Syncline
(5) David M. Scotford: The Sugarloaf Mountain Anticline, Maryland, and its place in the stratigraphic sequence
(6) Ernst Cloos: Tectonics in the Potomac River Gorge at Harpers Ferry, West Virginia
(7) Robert Balk: Deformation structure of the Grand Saline Salt Dome, Texas
(8) J. Tuzo Wilson: Lake's hypothesis as a basis for a system of geology (by title)

The meeting was adjourned at 12^h15^m

WILBUR S. BURBANK, Secretary

American Standards Association--Fred Anderegg, AGU representative on the Committee on Photography Z38 of the ASA advises that the latest approved standards are as follows:

Z38.1.3-1948 (revision of Z38.1.3-1941), American standard dimensions for 70-mm perforated (and unperforated) film, provides a film for still pictures and various scientific instruments such as oscillographs, electrocardiographs, seismographs and others.

Z38.1.50-1948, American standard dimensions for radiographic intensifying screens, covers any type of screen to be used in direct contact with x-ray film.

Z38.8.11-1948, American standard for photographic grade thermometers, covers thermometers of a grade suitable for use in the measurement of photographic solution temperatures whether of the fluid or bimetallic type.

Z38.8.19-1948, American standard method for determining maximum safe temperatures for photographic processing solutions, defines a test method for determining approximately the maximum safe processing temperature for a given photographic material.

SPECIAL ANNOUNCEMENTS

Publications of the International Associations--Publications of the International Associations of the International Union of Geodesy and Geophysics relating to the General Assembly in Oslo in 1948 are in preparation. Differing policies exist with respect to these, and they will be sent to the adhering countries in varying numbers. In Geodesy, the papers are published in Bulletin Geodesique which is available on subscription only. In other cases, AGU will be supplied with a limited number without charge, with, presumably, others available at a nominal sum. AGU will distribute these at cost (including handling and postage) to addresses in the United States (as the American National Committee of the IUGG). Those desiring copies of the publications of one or more of the Associations should advise AGU, indicating their willingness to commit themselves to the cost items involved. At the present time, the publication of the material of the Association of Terrestrial Magnetism and Electricity is advancing rapidly, and will consist of 500 to 600 pages. If no more than the free copies are required for distribution in the United States of America, the cost will probably not exceed fifty cents. If additional copies must be purchased, the cost will be distributed evenly over the entire number and probably will not exceed $1.00. Write promptly (at latest July 20, 1949) if you have interest in securing any of these. This relates both to members and subscribers.

Thirty-First Annual Meeting--The Thirty-First Annual Meeting of AGU will be held in Washington, D. C., May 1-4, 1950. Begin laying plans now for attendance and for any paper that you desire to present. Watch the SPECIAL ANNOUNCEMENTS in subsequent issues for further information such as closure dates for titles and abstracts.

The issues of June and August 1949--Because of the backlog of papers that has accumulated in oceanography and more notably in hydrology, a greater proportion than usual of this issue and of the August issue will be devoted to papers in these fields, in order to place authors in these fields on approximately the same basis of publication as authors in the other fields.

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